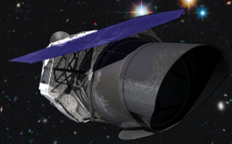
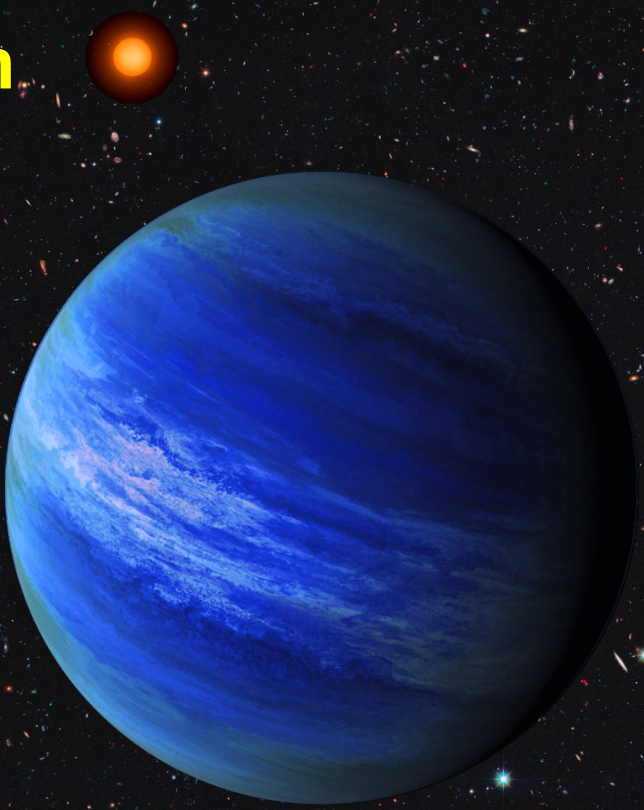


Imaging Exoplanetary Systems with the WFIRST Coronagraph Instrument



Dr. Vanessa Bailey

Jet Propulsion Laboratory

California Institute of Technology

Nov. 2, 2018

© 2018 California Institute of Technology. Government sponsorship acknowledged. The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The decision to implement the WFIRST mission will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

Outline

- Overview of exoplanet detection methods
- Exoplanet direct imaging with current instruments
- WFIRST + CGI

WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

Science Drivers

- Is our Solar System unusual?
- How common are planetary systems?
- How did our and other Solar Systems form?

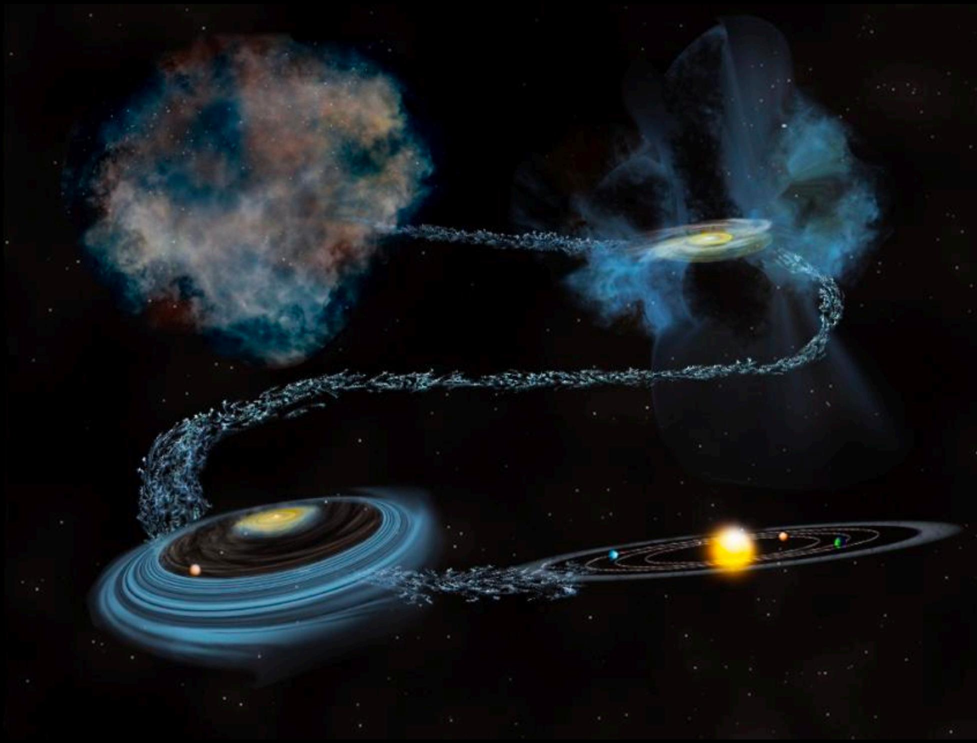
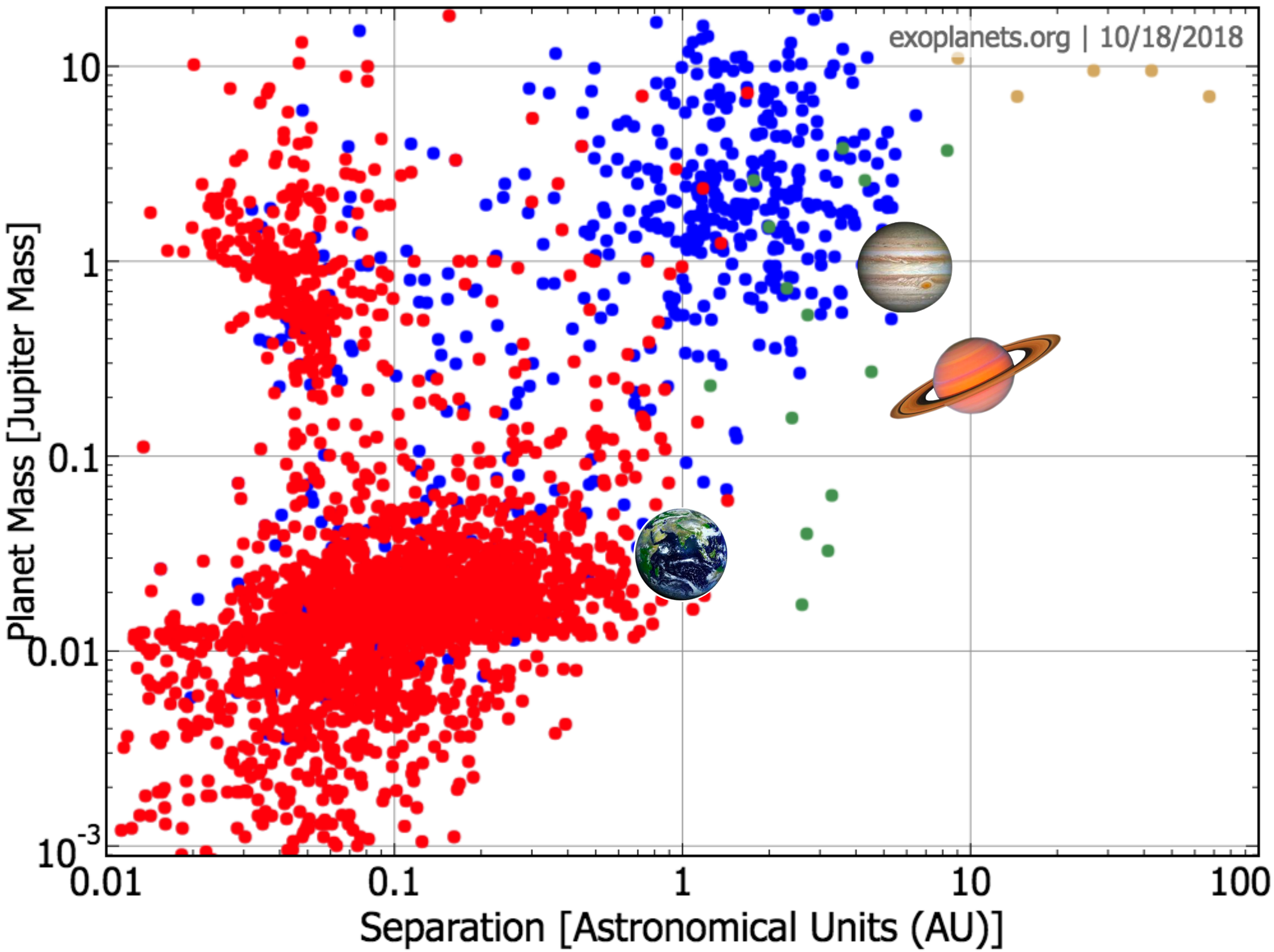


image credit: Bill Saxton, NSF/AUI/NRAO

Exoplanets known today



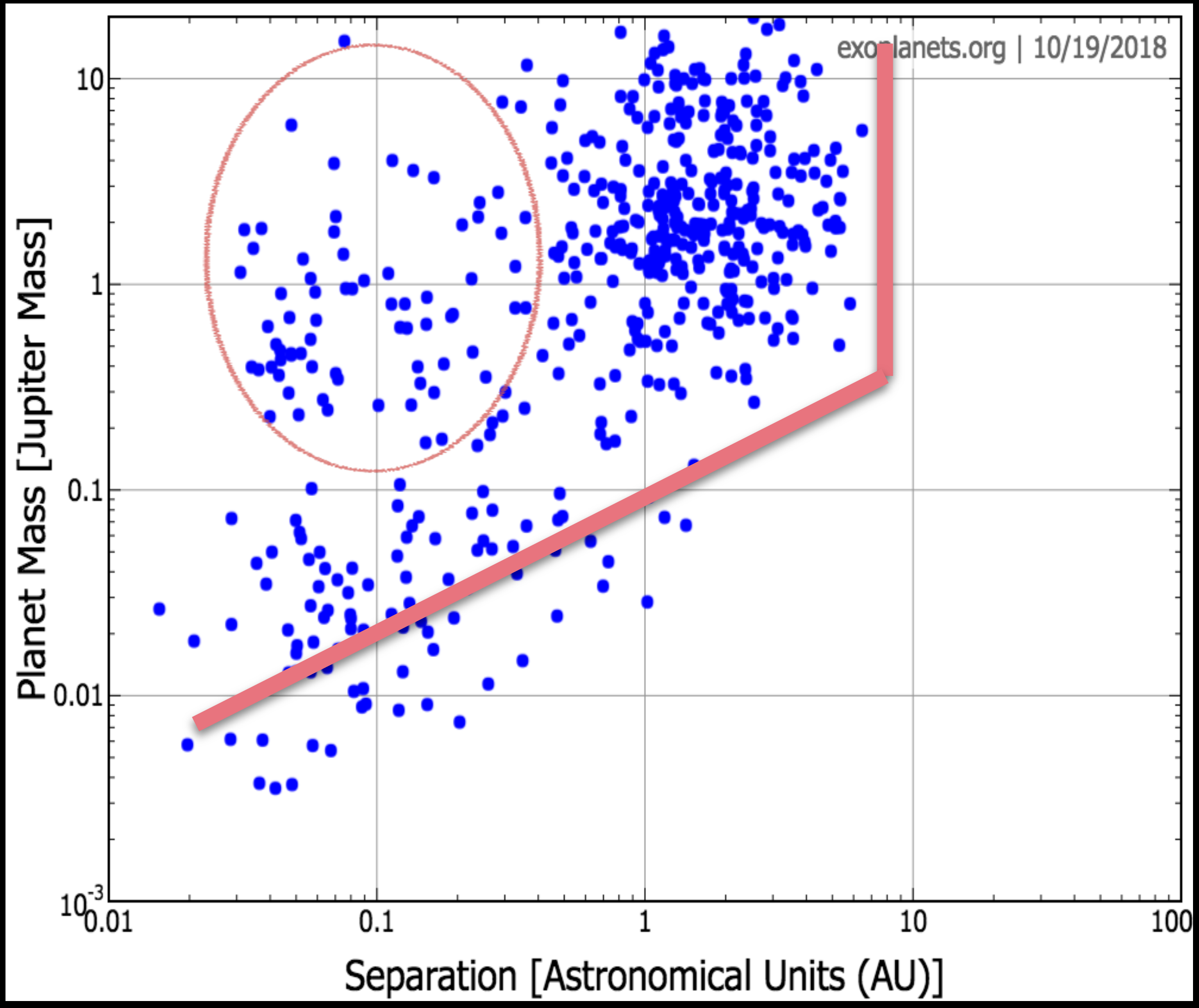
Indirect Methods of Finding Exoplanets

Radial velocity measures mass & period

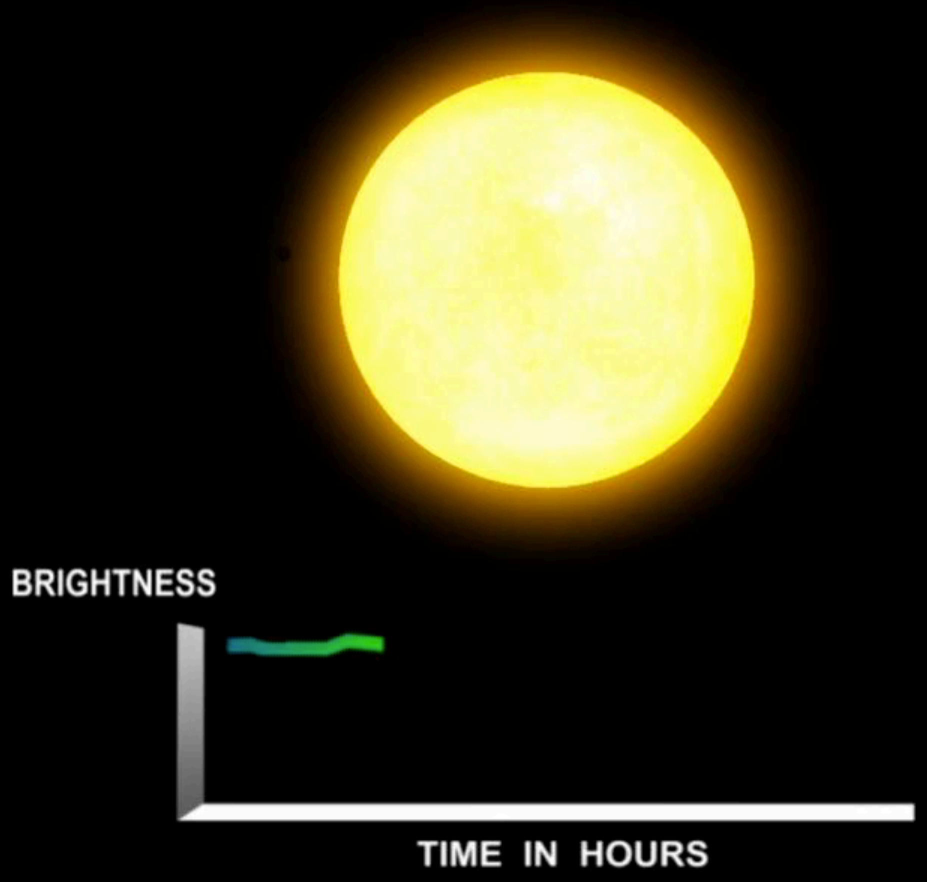
Credit:ESO/L. Calçada

RV selection bias: massive planets and short orbits

planet frequency increase with separation



Transits measure radius and period

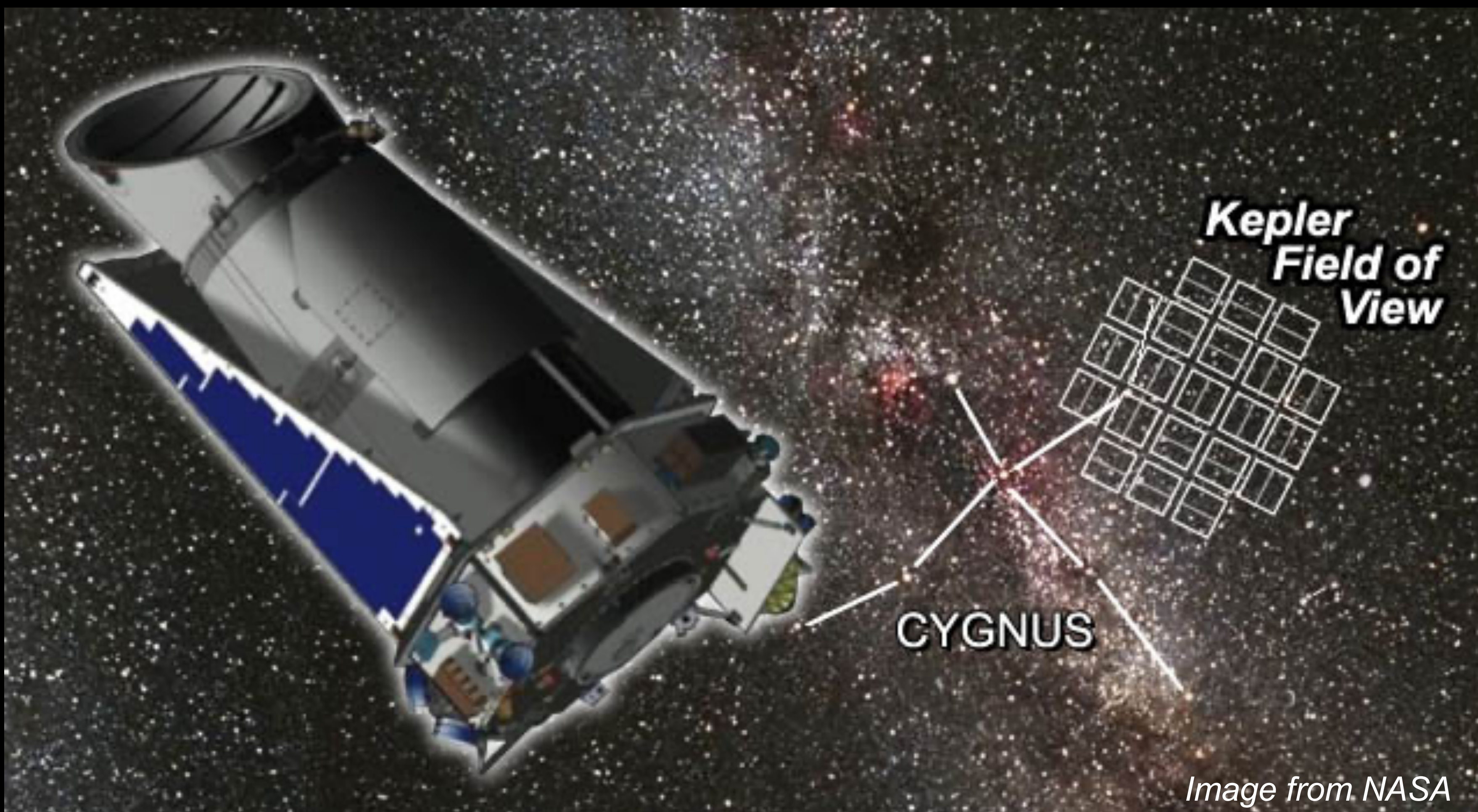


Credit: NASA Kepler Mission/Dana Berry

Kepler (main mission)

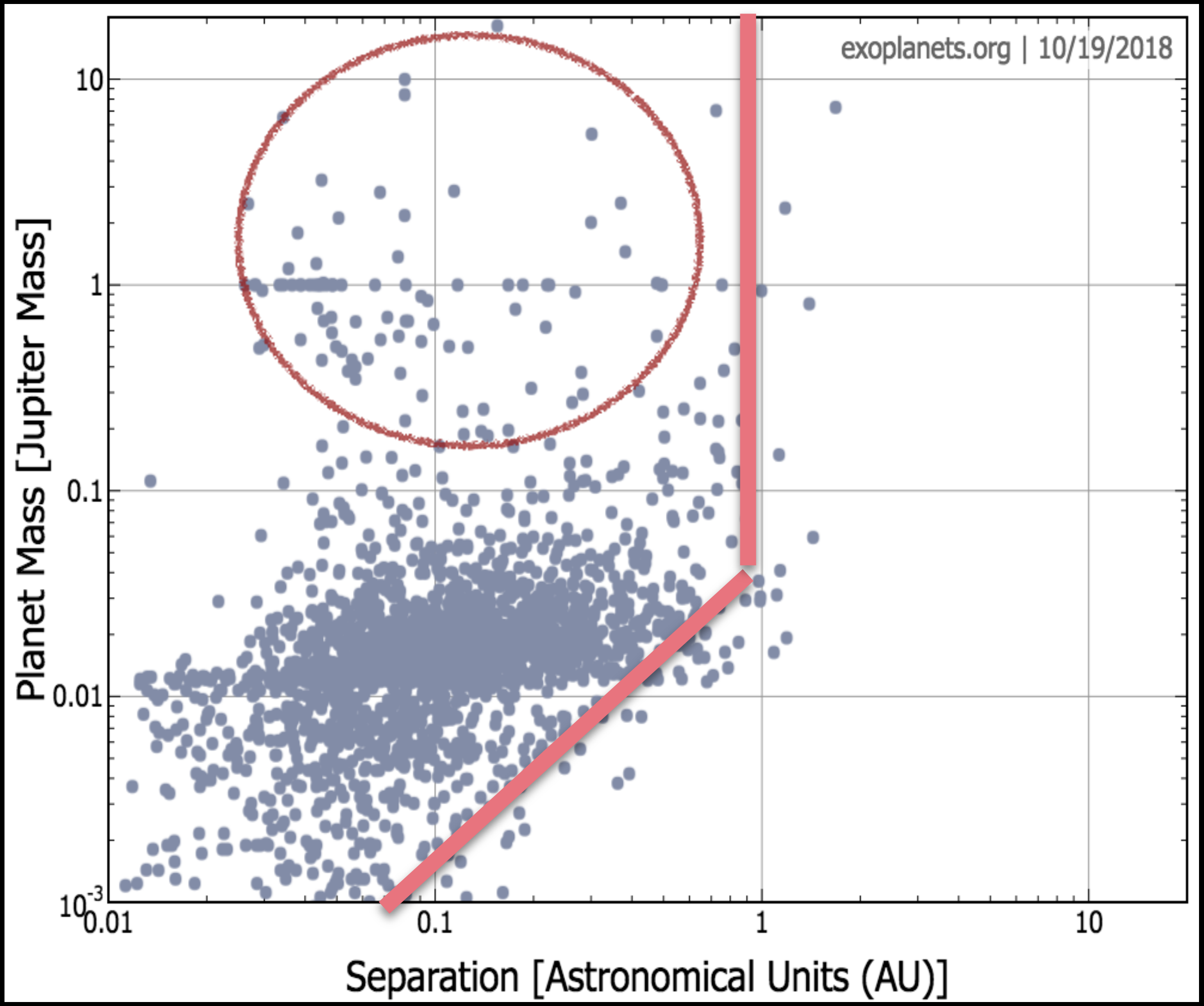
150,000 stars
Continuous monitoring

High precision photometry



transit selection bias: large planets and short orbits

Hot Jupiters are rare. Hot and warm **Super Earths** are common



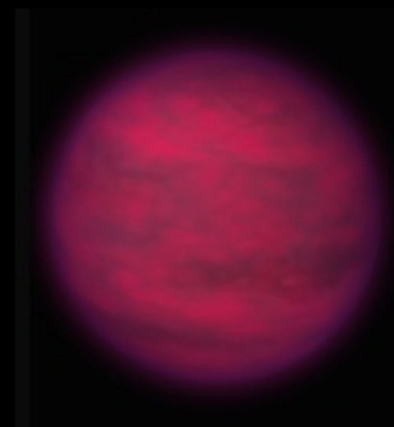
Most stars have planets

Image credit : wikipedia

New discoveries: Objects **not** in our solar system

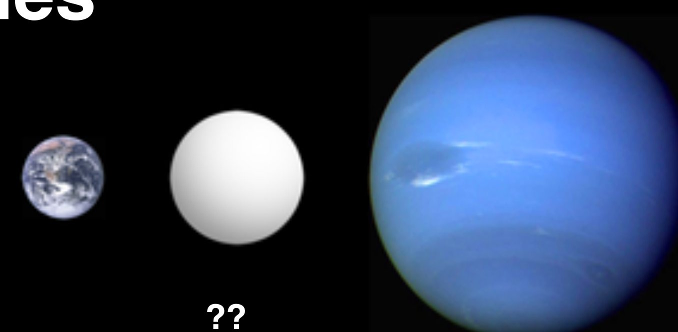
Brown Dwarfs

- $\sim 13\ M_{Jup} < M < \sim 75\ M_{Jup}$
- mostly H / He atm
- no core?

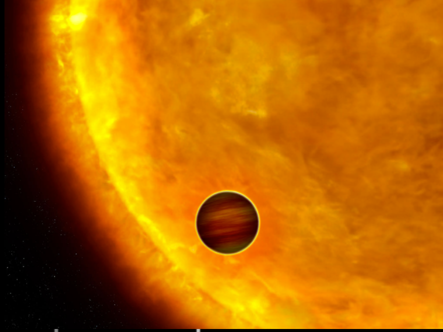


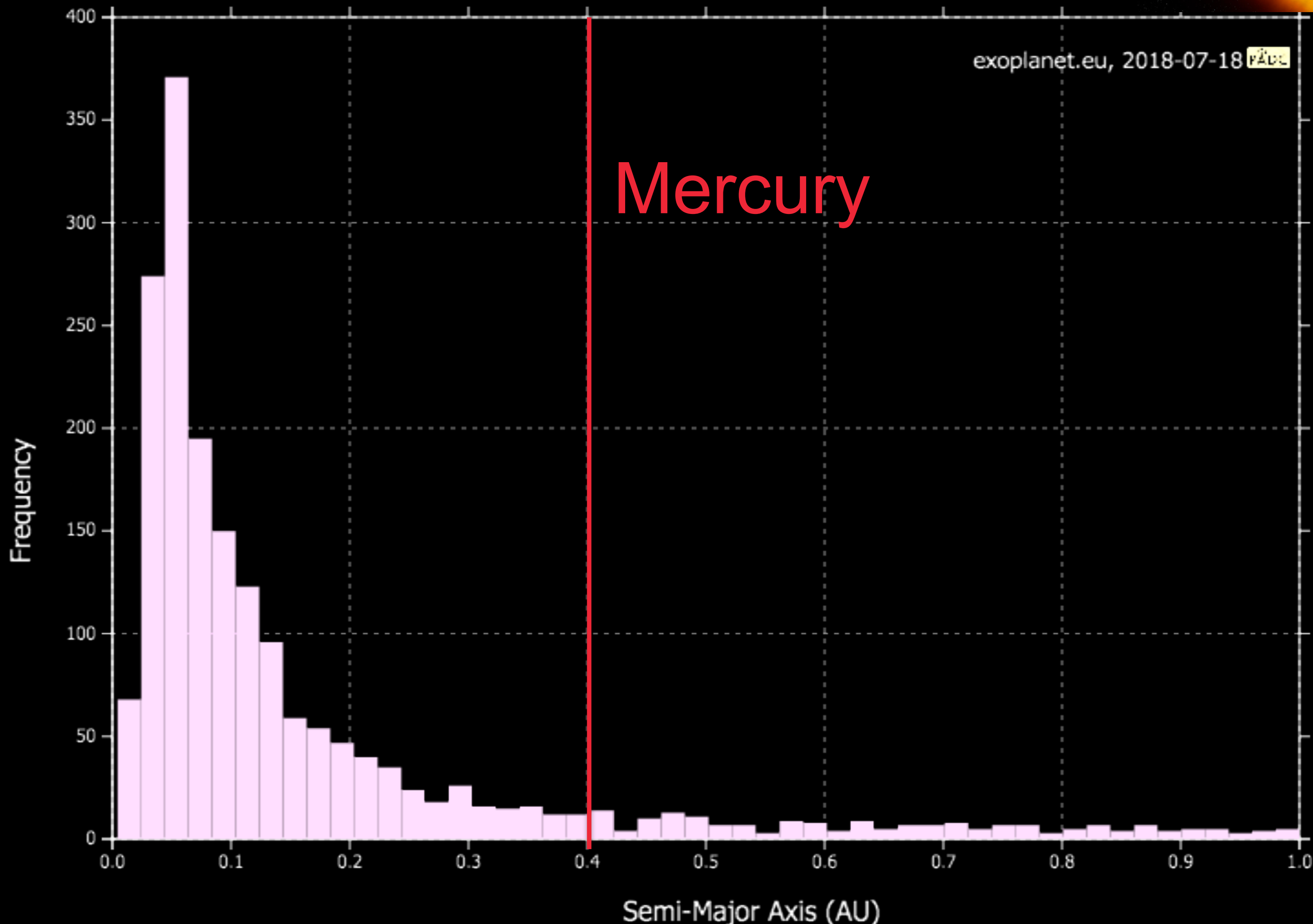
Super Earths / Mini Neptunes

- $\sim 2\ M_E < M < 10\ M_E$
- Rocky core
- atm = ???

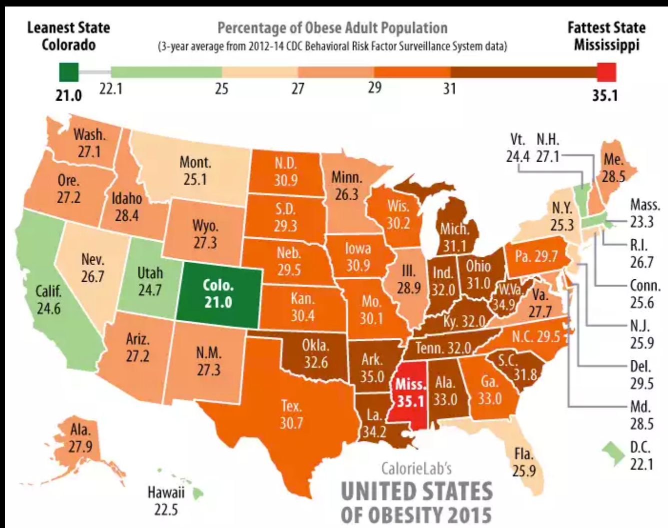


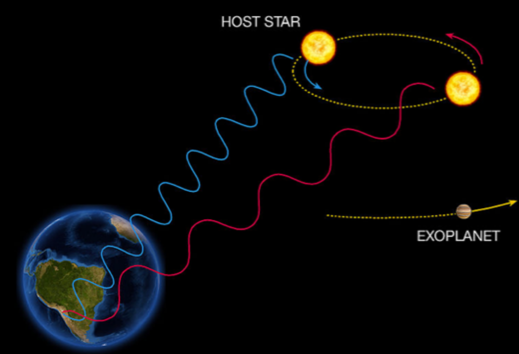
Most planets we know about are in orbits smaller than Mercury's

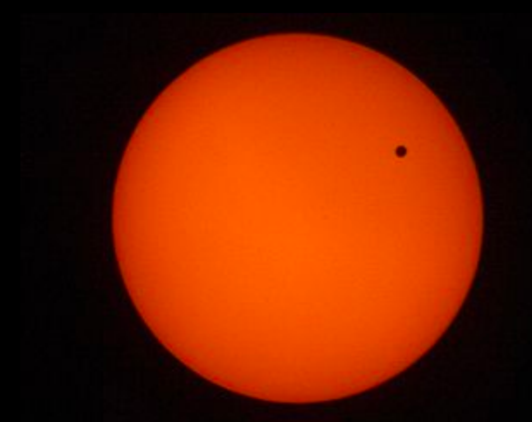




these prolific detection methods just* take a census







* Can characterize a handful of hot transiting planets!

Image credits: calorielab, ESO, Wikipedia (Mswggpai)

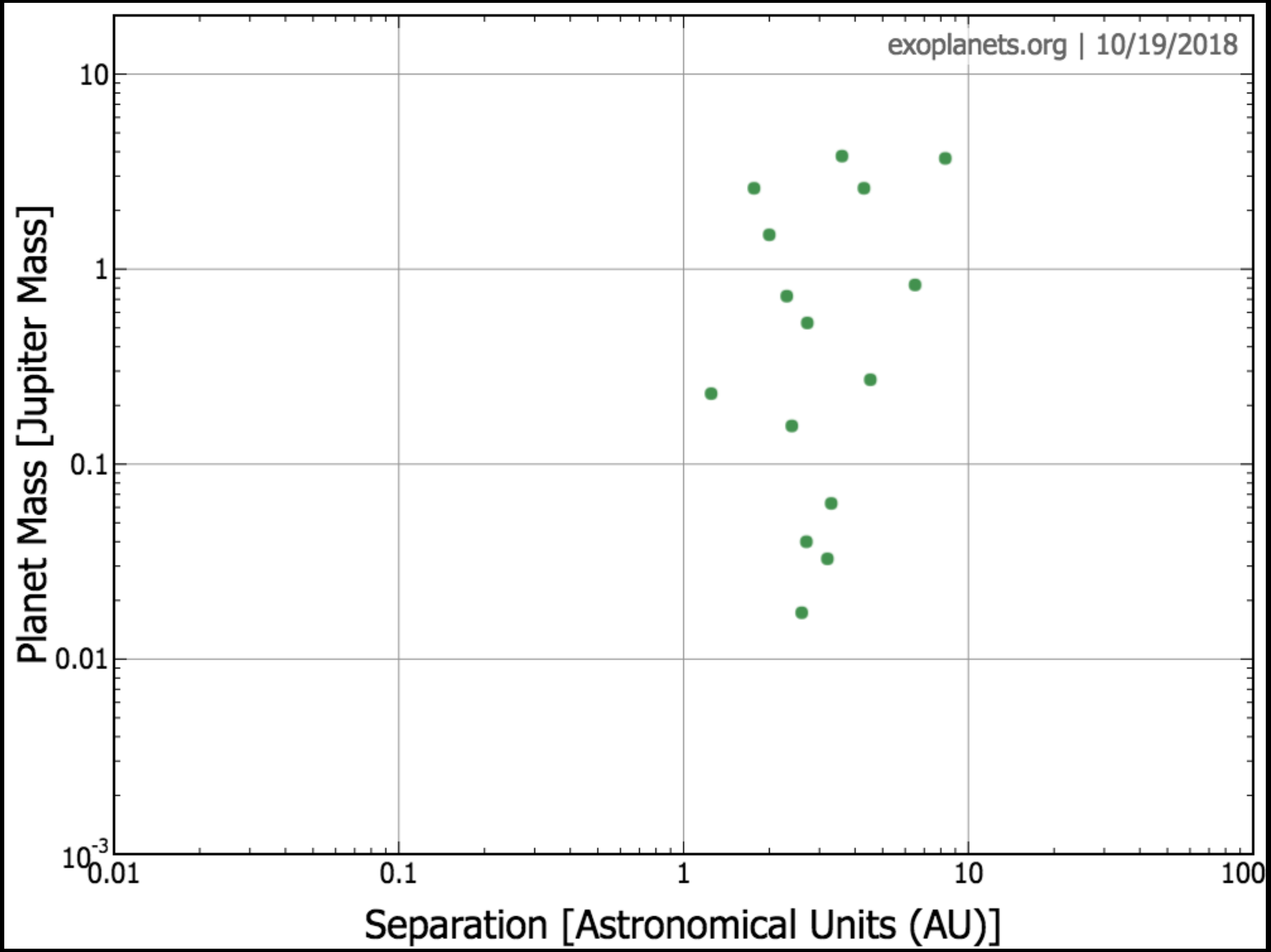
What if we want to study planets in the **outer reaches** of planetary systems?

Microlensing: one-off detections

www.eso.org

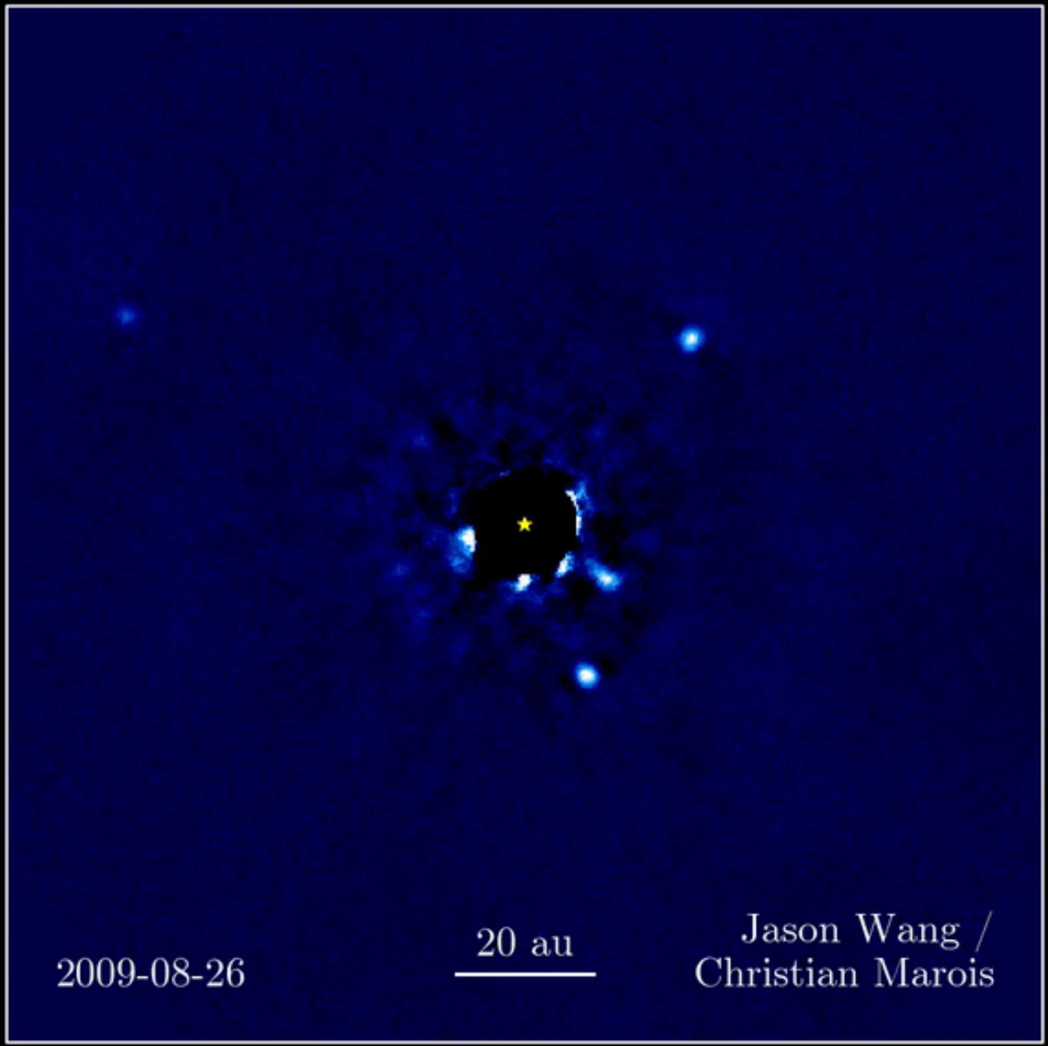
Credit:ESO/L. Calçada

Microlensing selection bias: ~ 1-10au orbits

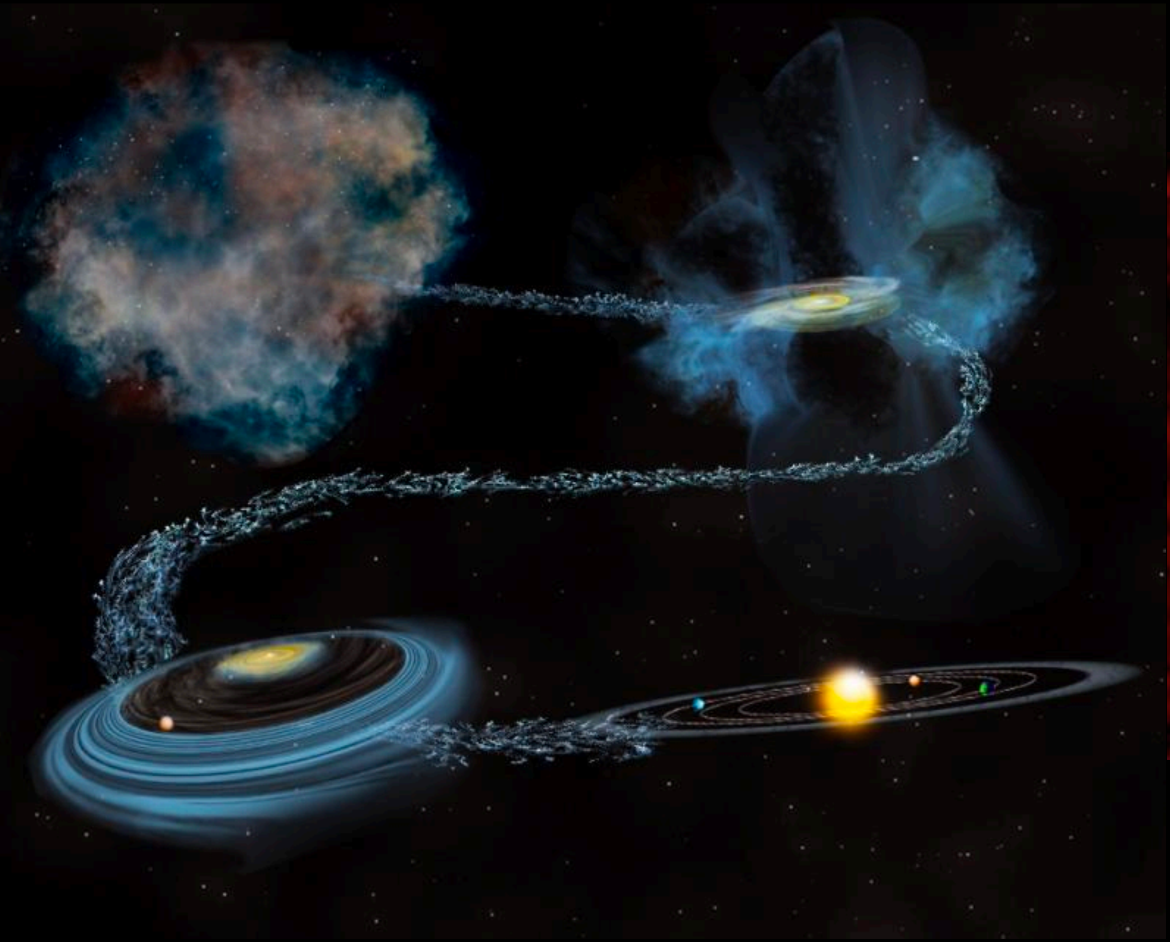


What if we want to know **details** about wide-separation planets or their surroundings?

We just* take a picture!

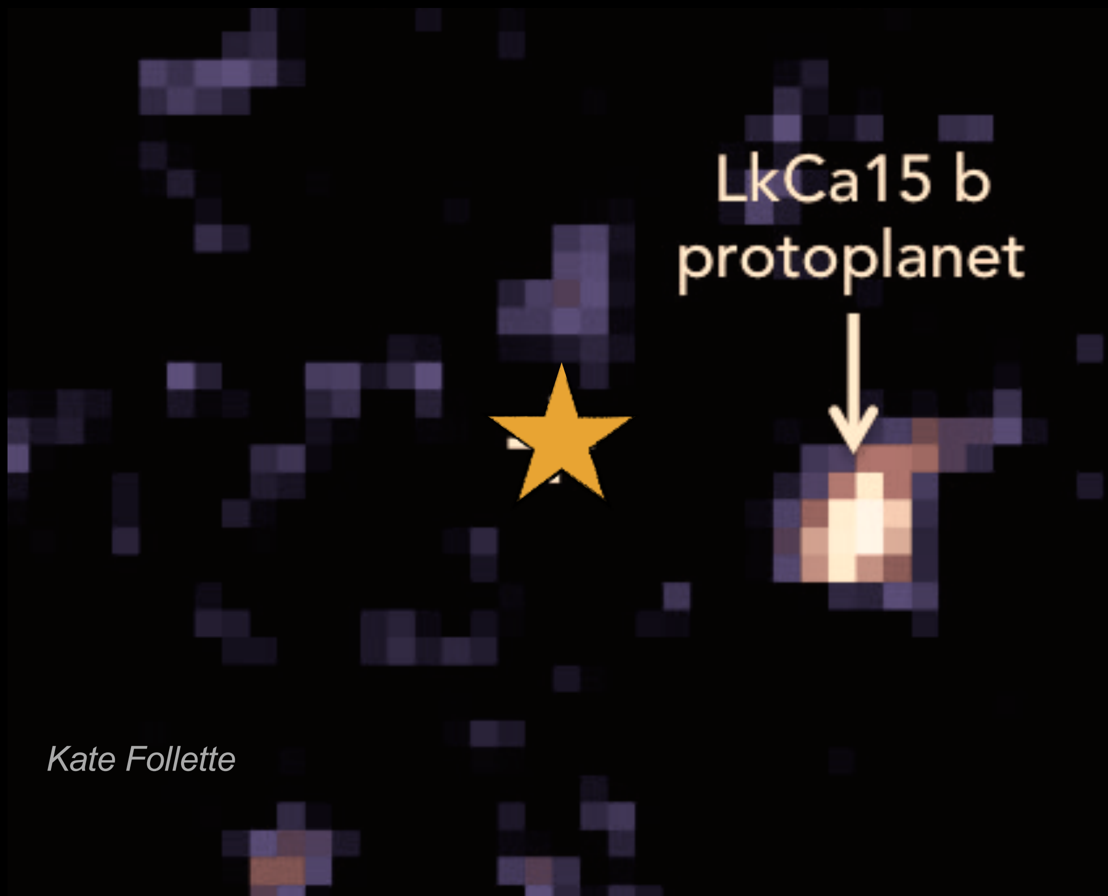


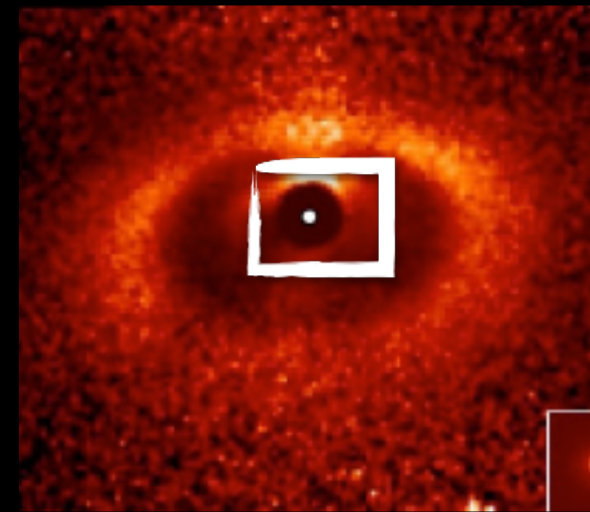
Catching planets in the act of formation



What is causing this gap in the disk?

image credit: Bill Saxton, NSF/AUI/NRAO



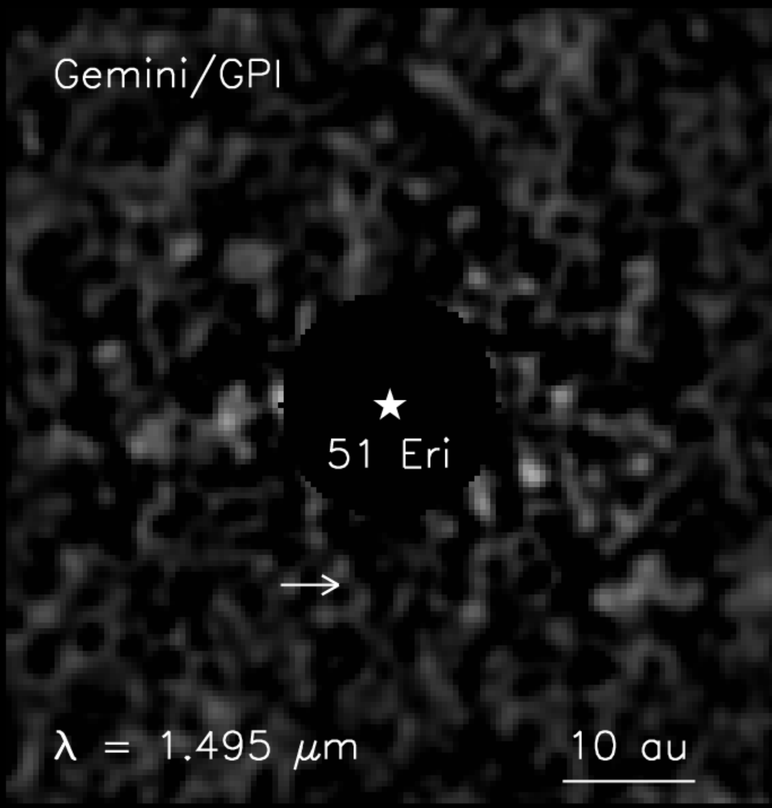


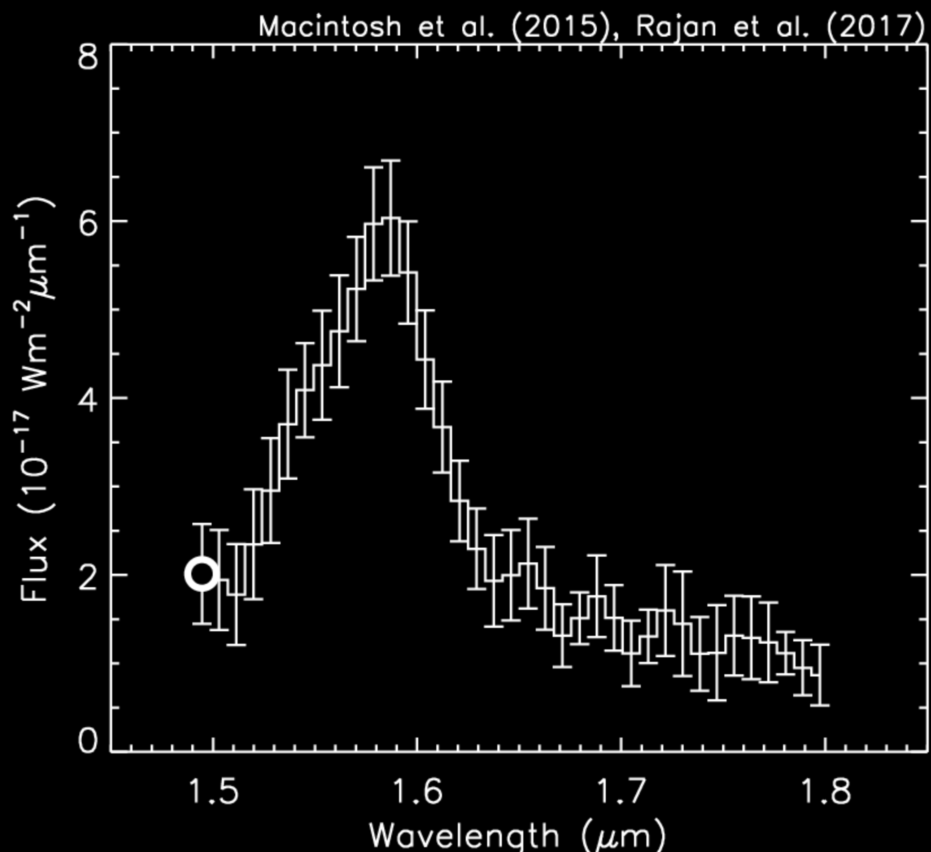
First photo of a baby planet

giant

Thalmann+2016; Sallum, Follette,+2015

Spectra show molecular absorption signatures





Credit: Rob De Rosa / GPIES

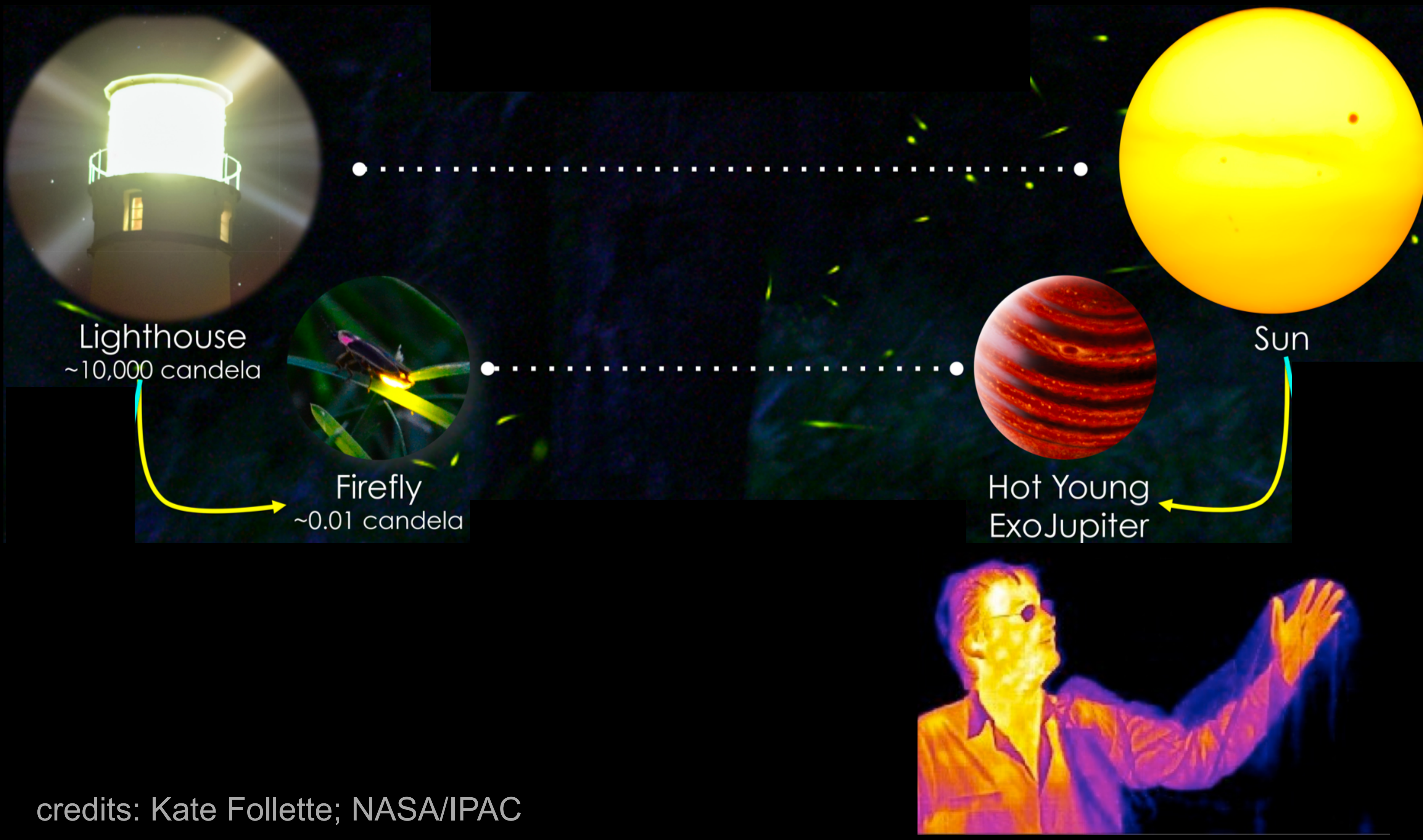
Planets are

faint

&

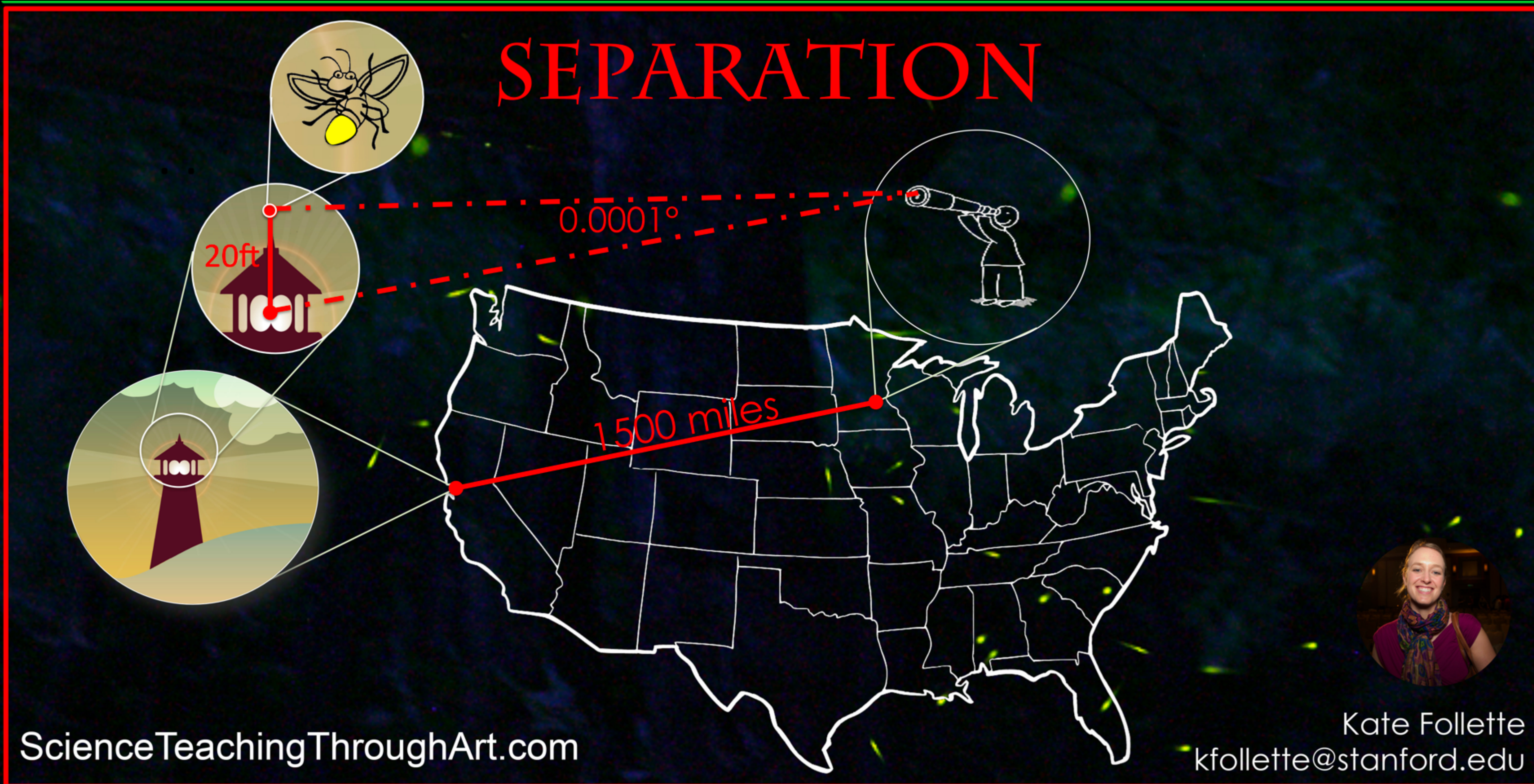
far, far away

"Bright" young super-Jupiters are 10^6 times fainter than their stars



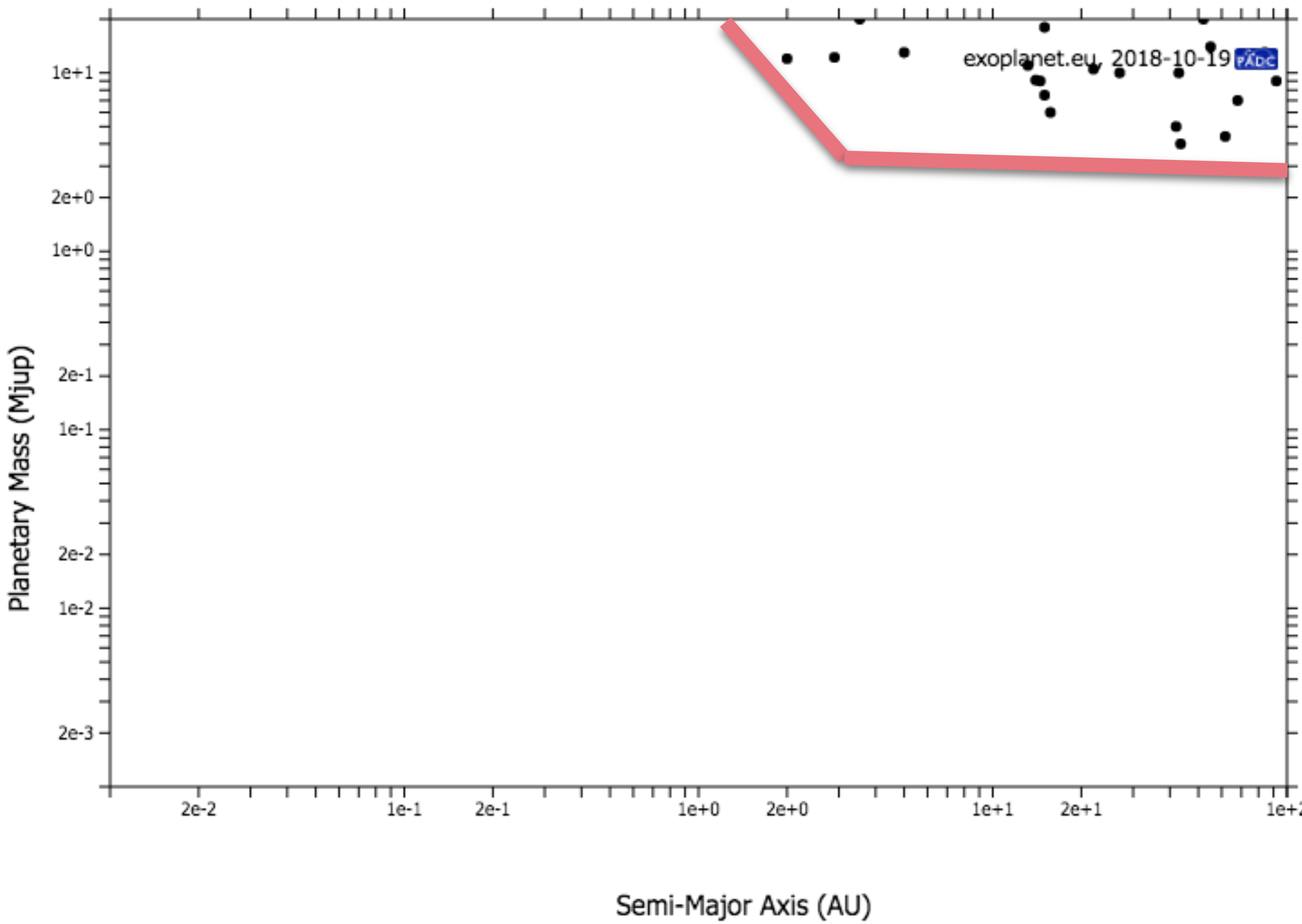
credits: Kate Follette; NASA/IPAC

Planets appear < 0.5" from their stars

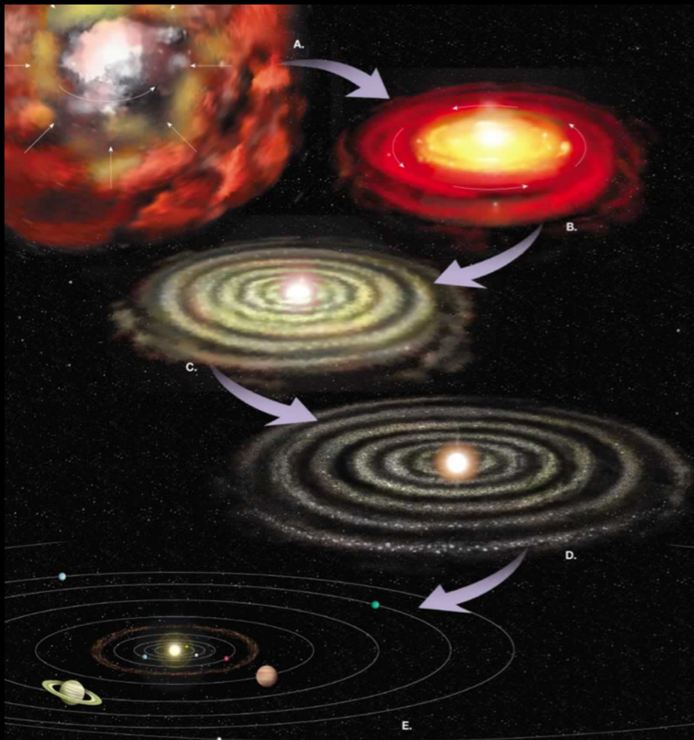


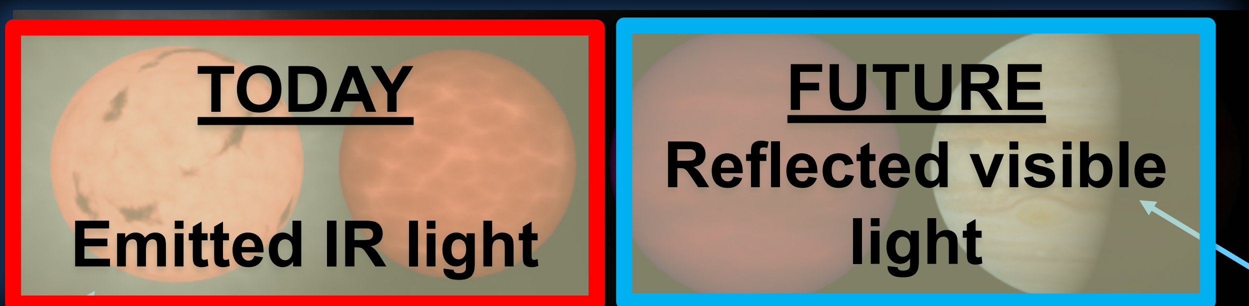
Adaptive Optics
“de-twinkle” the stars

Direct imaging selection bias:
large, young planets far from their stars



Young planets are hot and glowing, but cool with time





New planet: 1000-3000K

10 million years: 600K

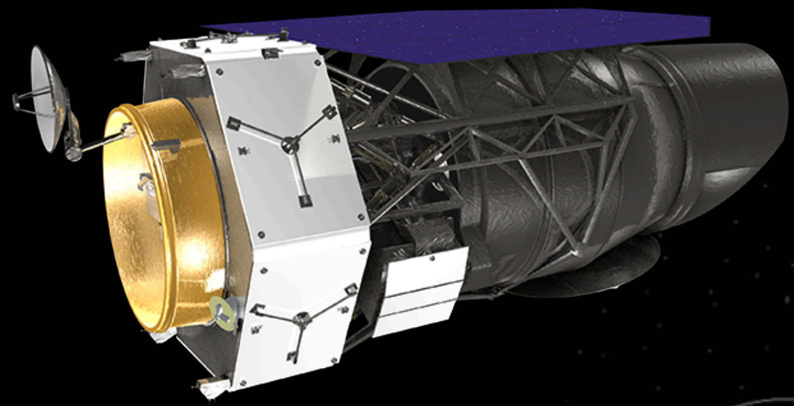
100 million years: 300K

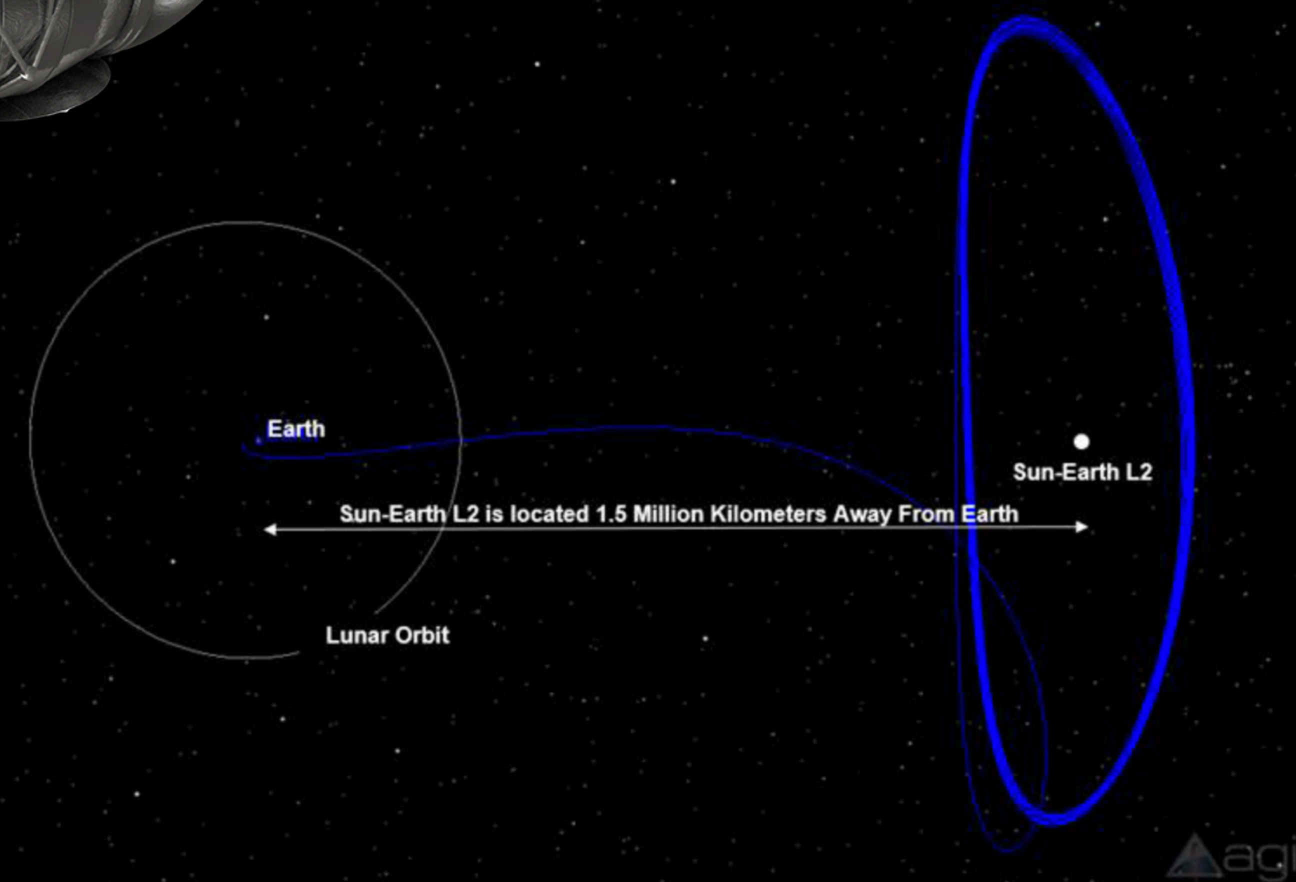
4600 million years: 110K

What do we need to
find and **characterize**
a Solar System twin?

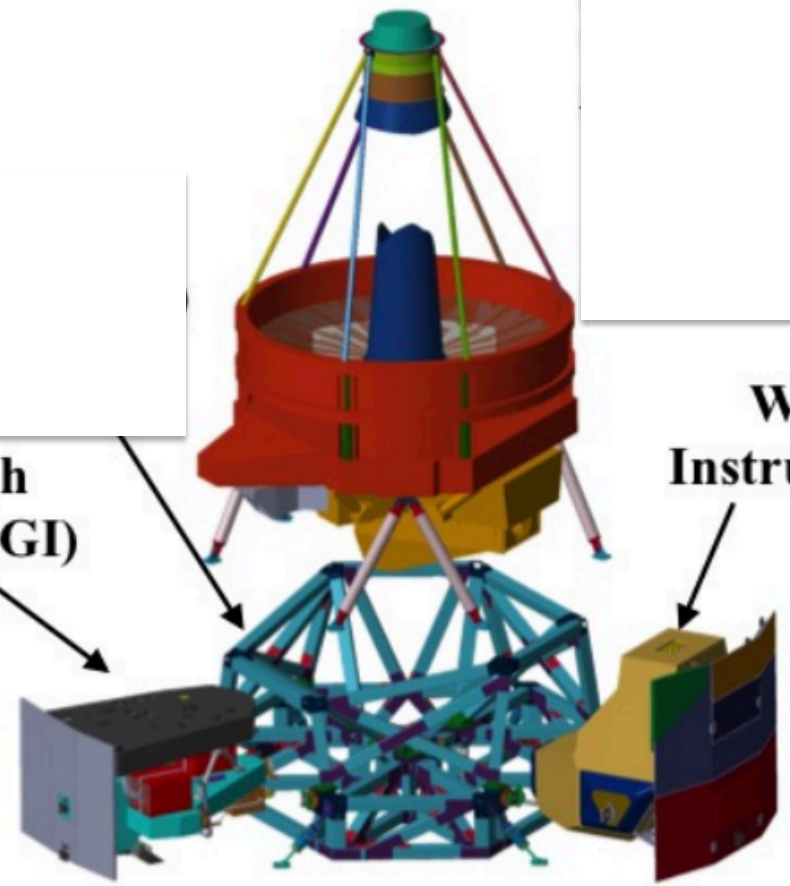
WFIRST
Wide-Field Infrared Survey Telescope
Astrophysics • Dark Energy • Exoplanets

WFIRST will launch 2025-2026 & orbit at L2





WFIRST has 2 instruments: WFI & CGI



Coronagraph Instrument (CGI)

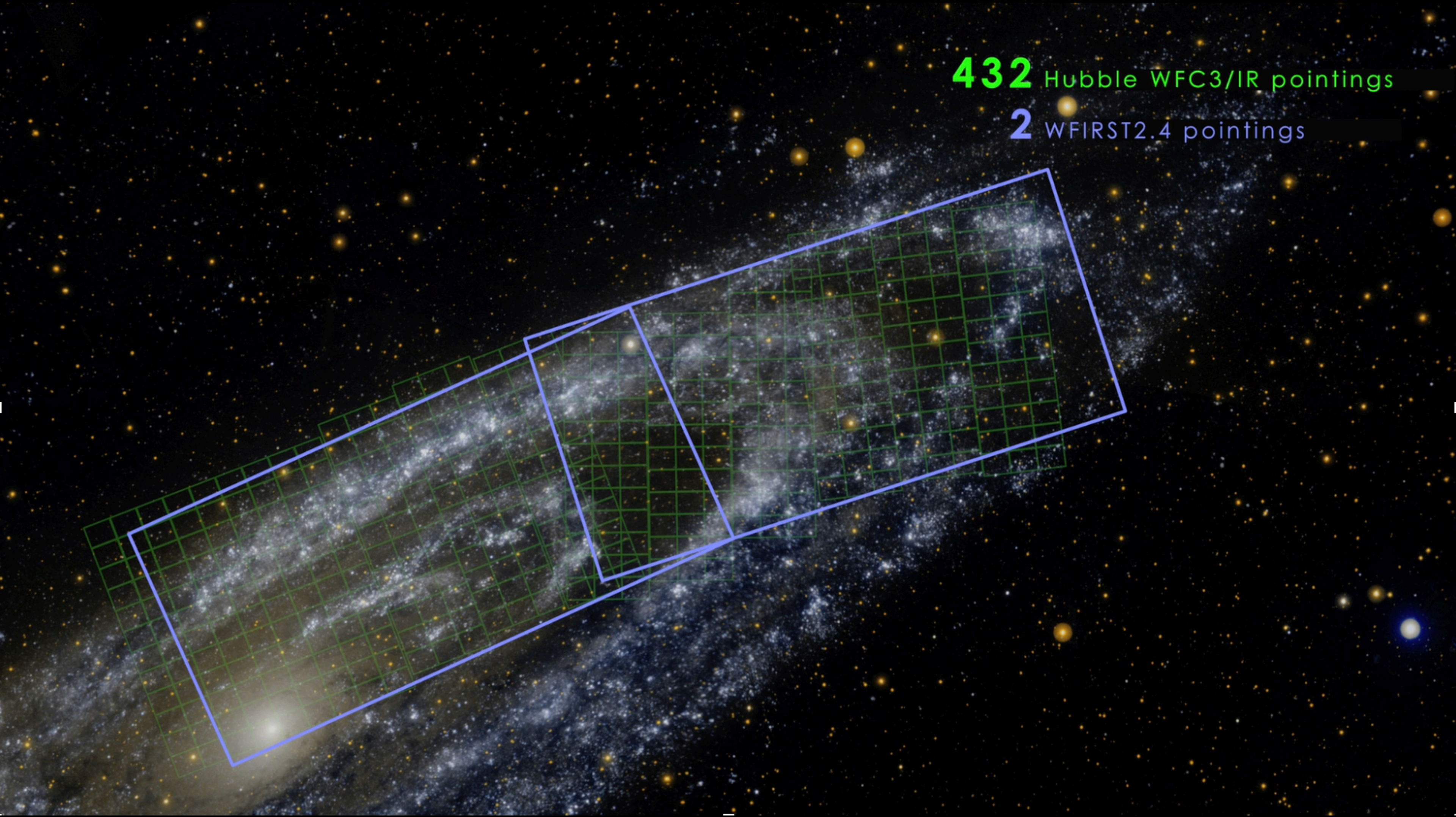
Visible light imager and spectrograph : direct imaging

Wide-Field Instrument (WFI)

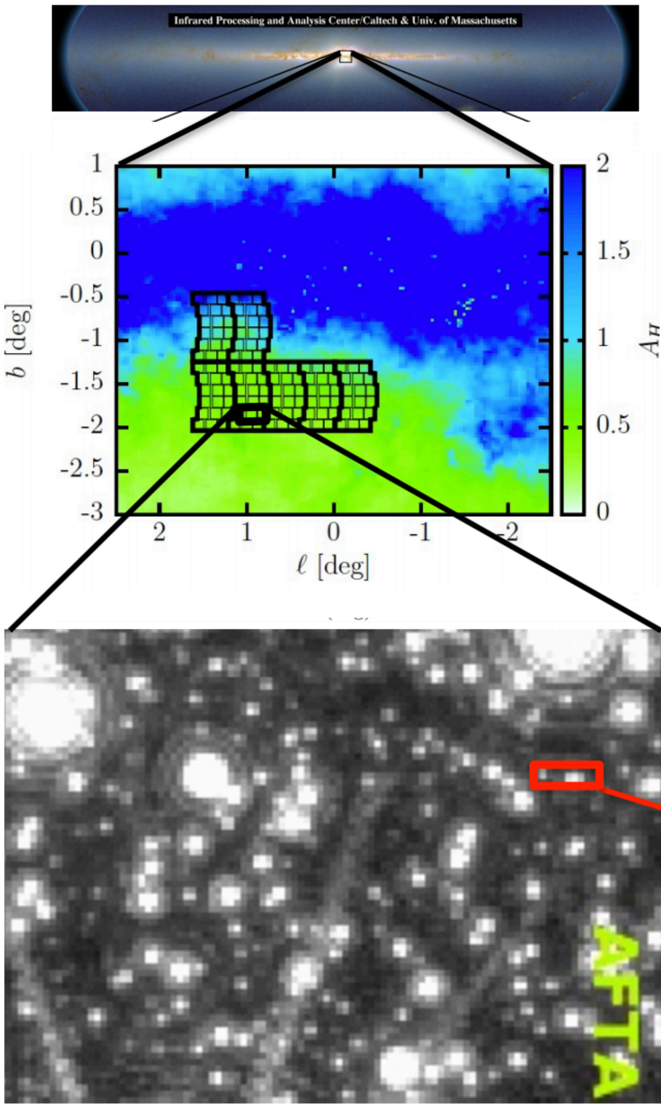
IR imager: Cosmology & microlensing

Expanded view of the WFIRST payload

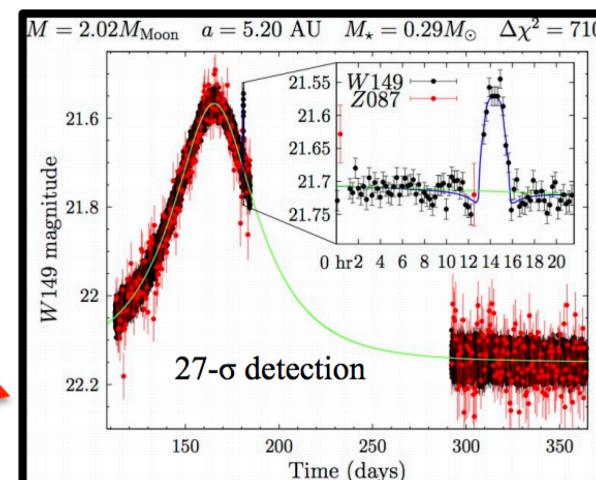
WFI : wide field of view near infrared camera



WFI microlensing survey



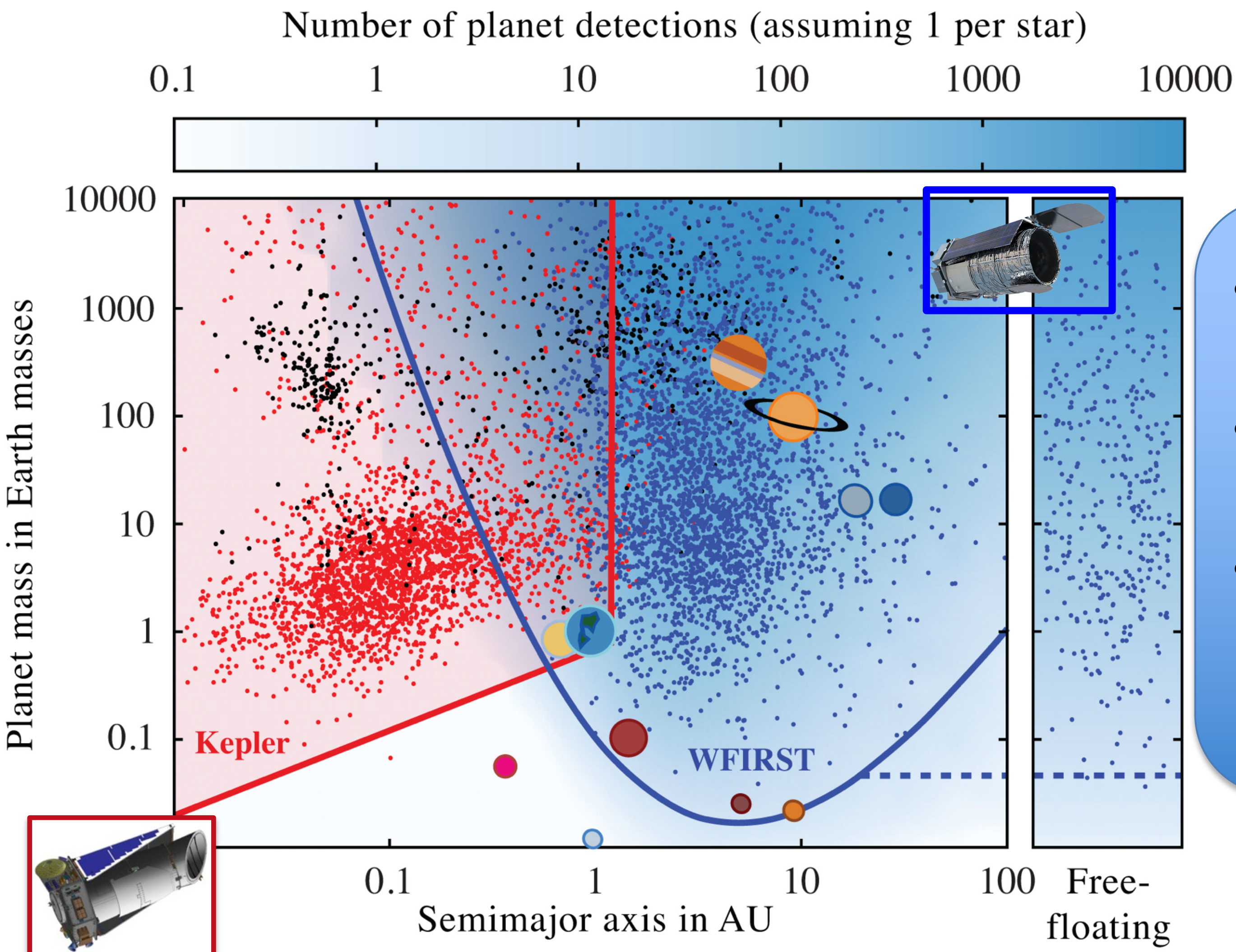
- Will monitor 7 fields of 0.28 deg^2 each
- Every 15 minutes (HZ Earth amplification anomaly is ~few hours long)
- With ~45s individual exposures in 2 filters:
  - 0.93-2 μm (W149) & 0.76-0.98 mm (Z087)
- High precision photometry on short timescales enables detection of weaker signals: smaller planets, HZ planets



(Penny et al., in prep)

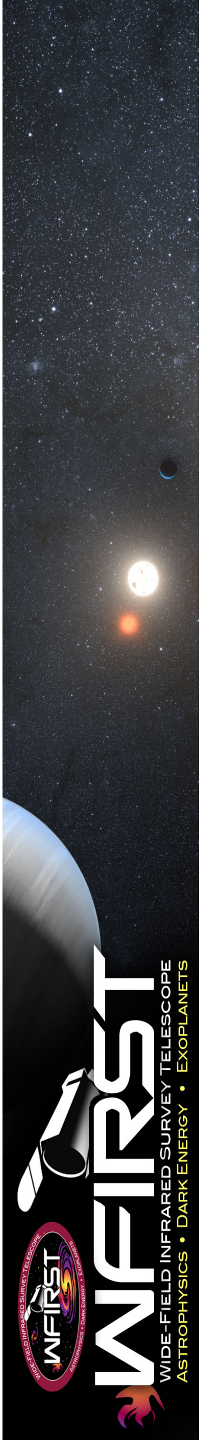
WFI microlensing

complements Kepler, TESS, PLATO



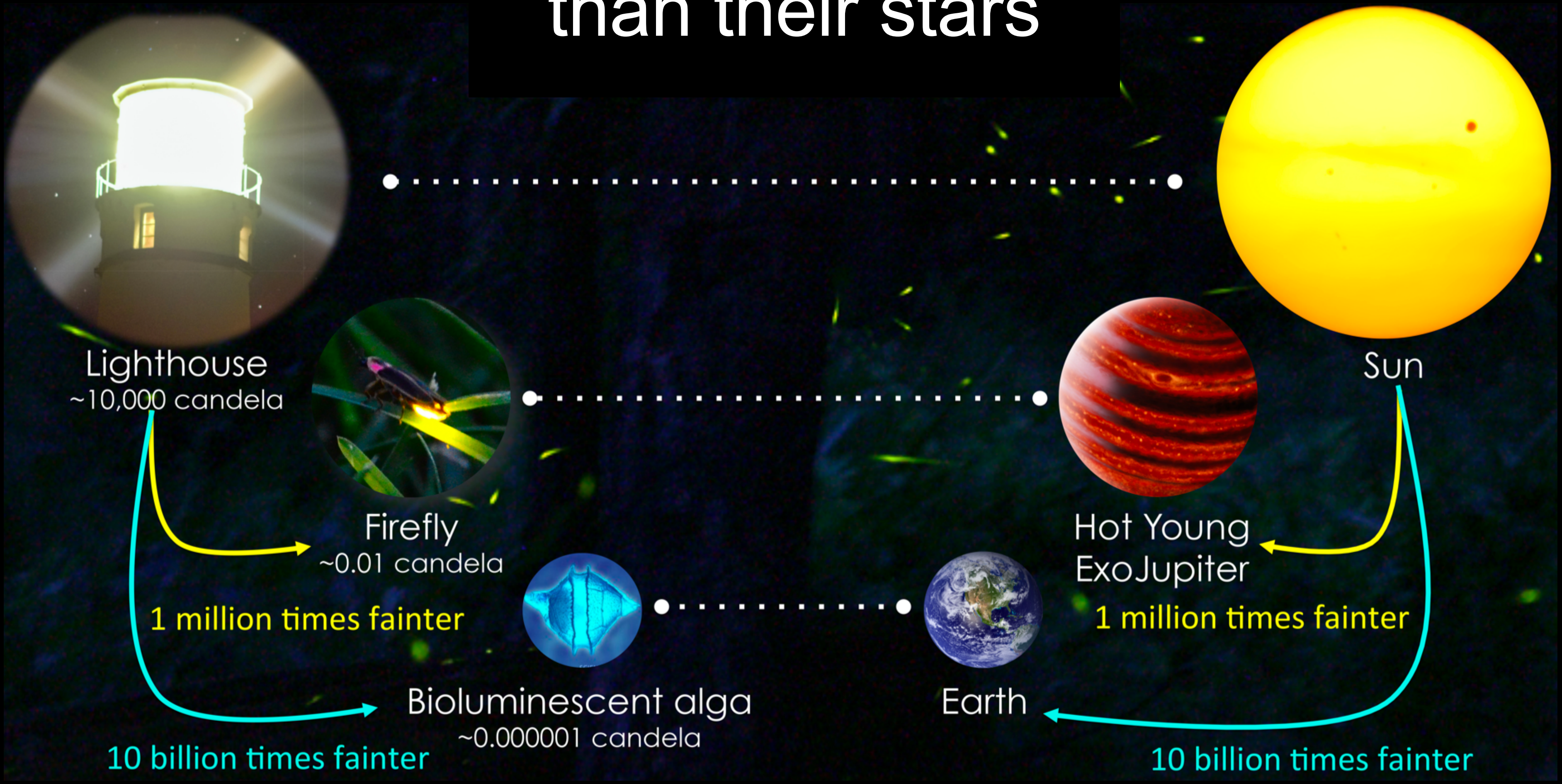
- 2600 planet detections.
- **370 with < 1 Earth mass**
- Hundreds of free-floating planets.

M. Penny (OSU)



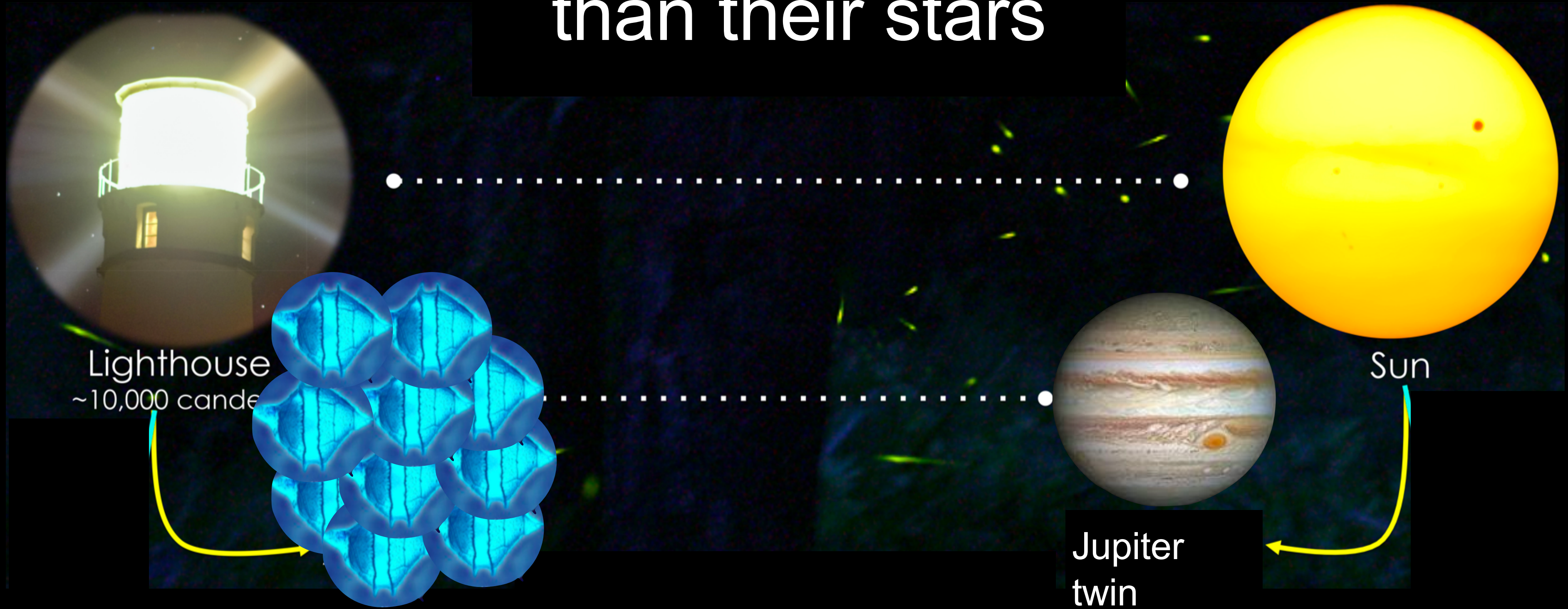
Coronagraph Instrument (**CGI**) is a technology pathfinder for future imaging and spectroscopy of Earth-like planets

Earth Twins are $10x10^9$ times fainter than their stars



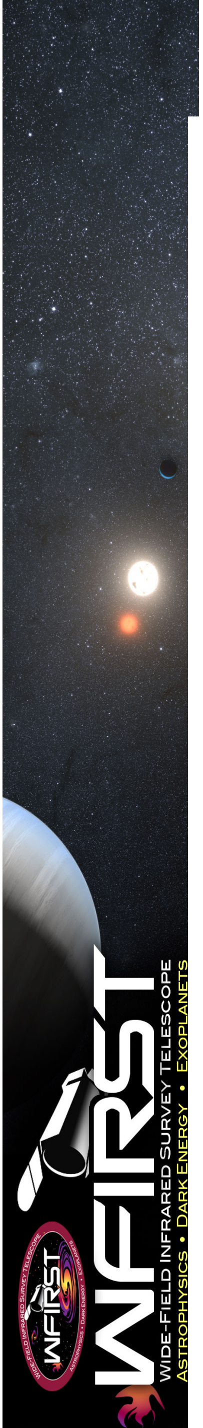
credit: Kate Follette

Jupiter twins are **10^9 times fainter** than their stars

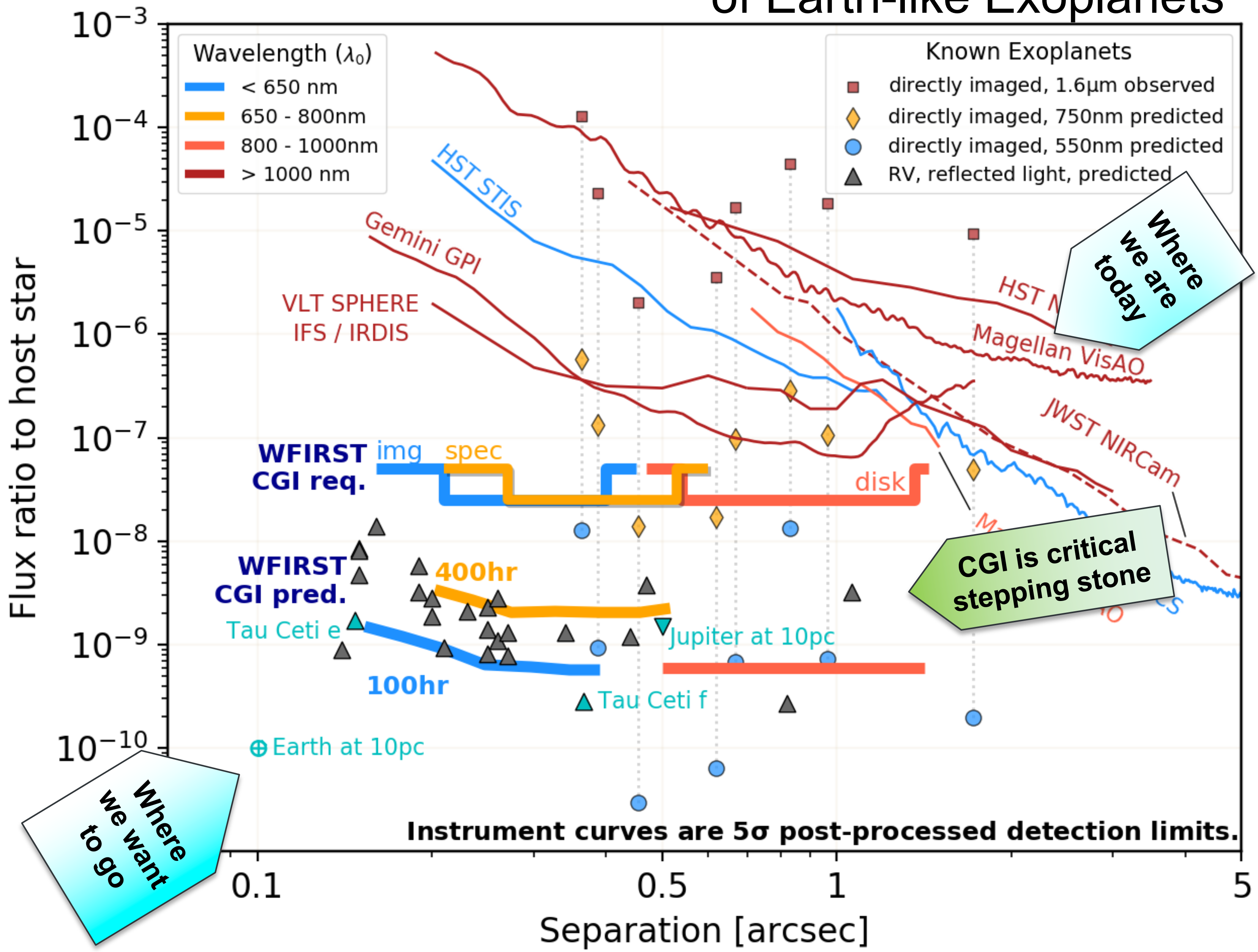


We can't remove atmosphere turbulence well enough to do this from the ground

credit: Kate Follette; with modifications

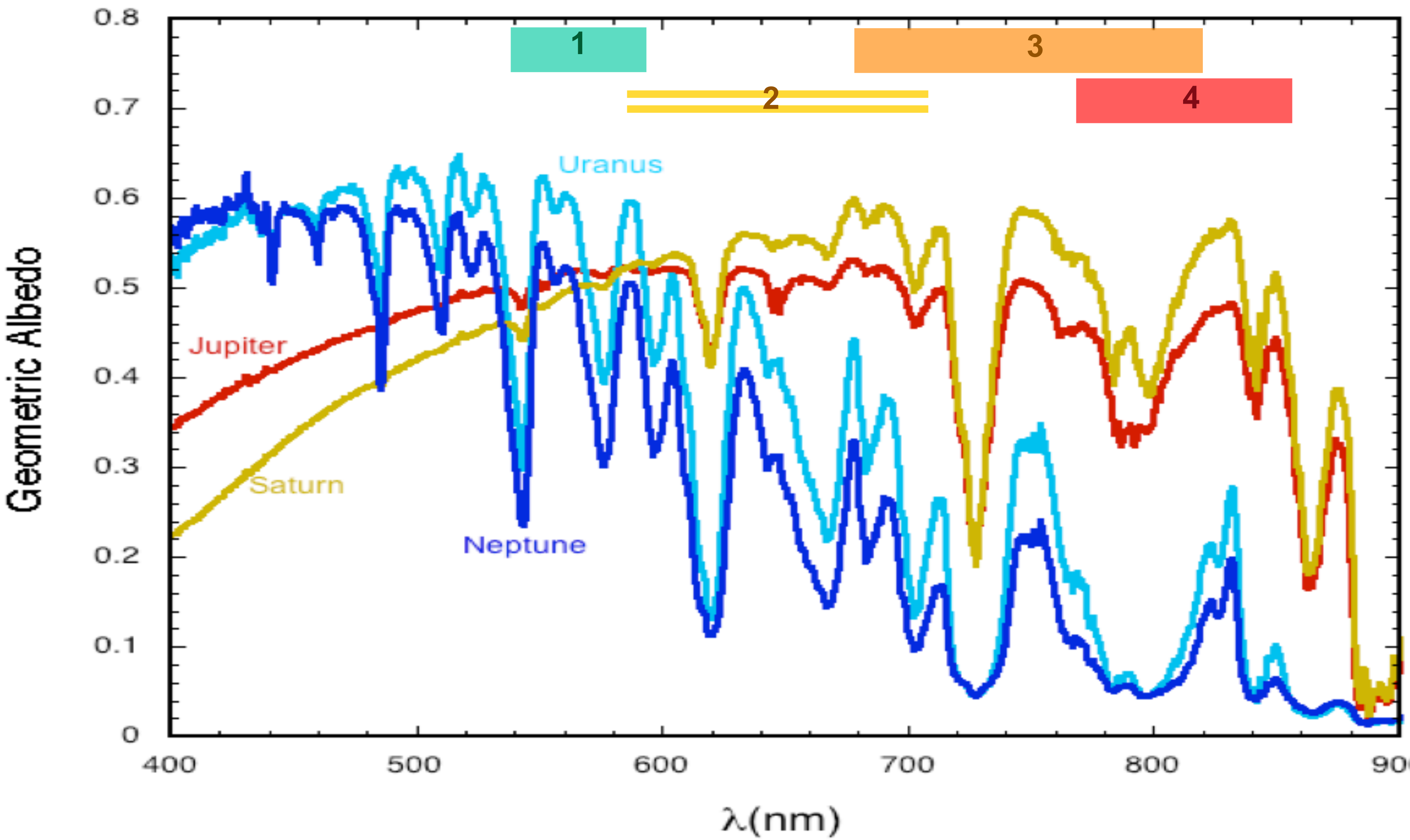


CGI is a Pathfinder for Direct Imaging and Spectroscopy of Earth-like Exoplanets



CGI is a visible light imager and spectrograph

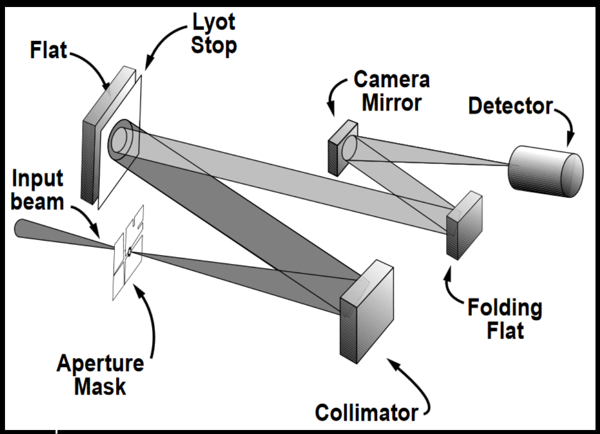
λ_1=575 nm, 10% λ_2=660 nm, 18% λ_3=760 nm, 18% λ_4=825 nm, 10%

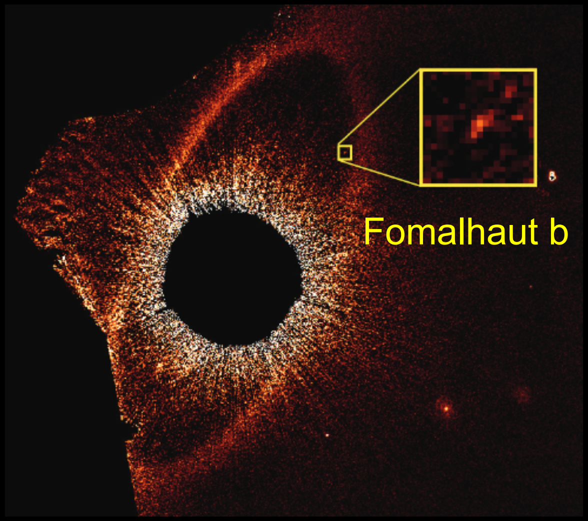


Imaging exoplanets with HST – no active optics

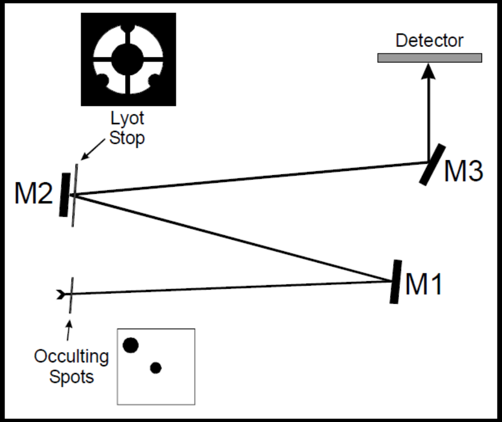
Hubble has had three Lyot coronagraphs used in its instruments to look at planets:

STIS

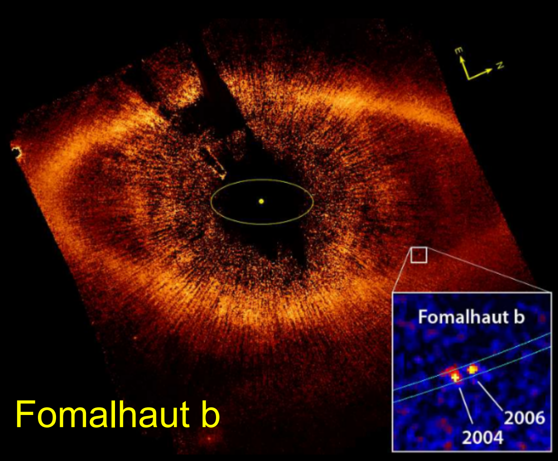




ACS/HRC

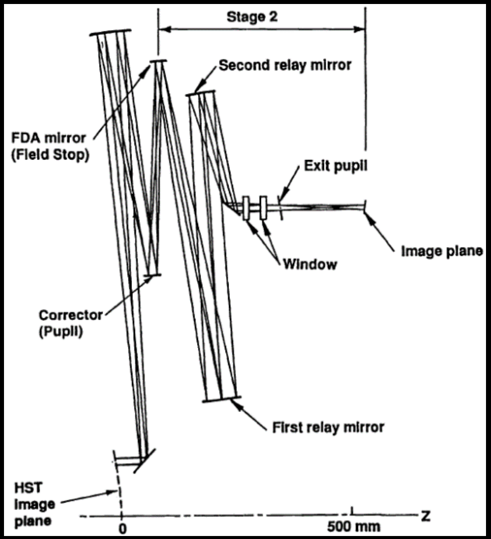


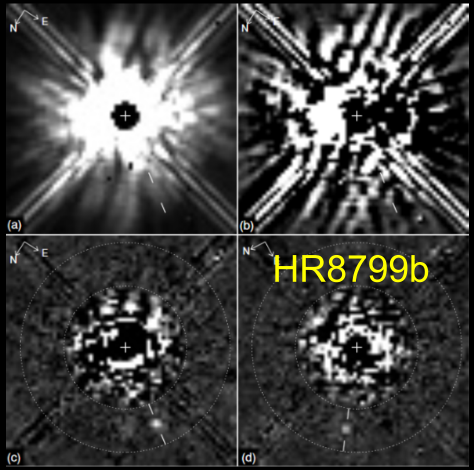
Krist *et al.* 2003



Kalas *et al.* 2008

NICMOS



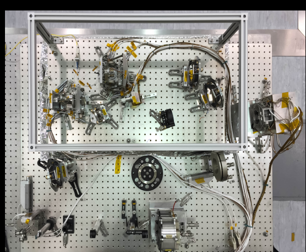


Lafrenière *et al.* 2009

WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

CGI will demonstrate key technologies for future missions

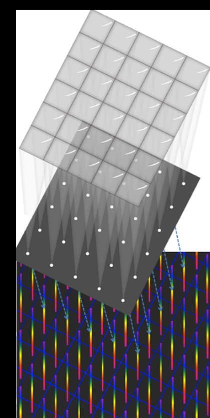
Autonomous Ultra-Precise Wavefront Sensing & Control



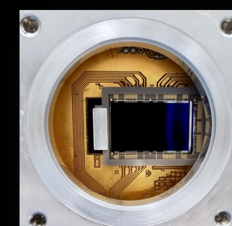
Large-format Deformable Mirrors

High-contrast Coronagraph Masks

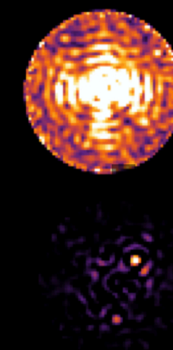
High-contrast Integral Field Spectroscopy



Ultra-low noise photon counting Visible Detectors



Data Post-Processing

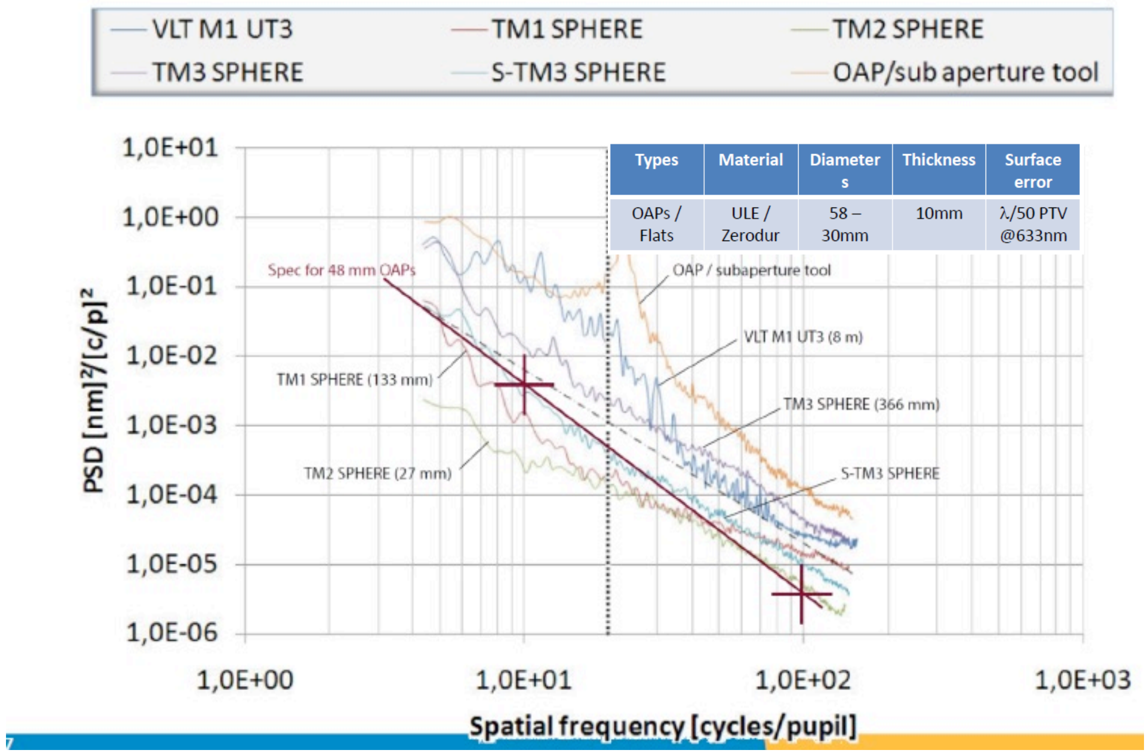


CGI is a “technology demonstration” instrument

Optics following the Deformable Mirror are Critical

- High precision off-axis parabolas to be provided by LAM using stress polishing techniques

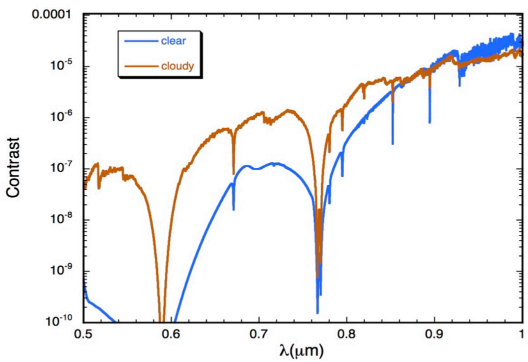
- Critical since post deformable mirror; need to maintain wavefront error accuracy



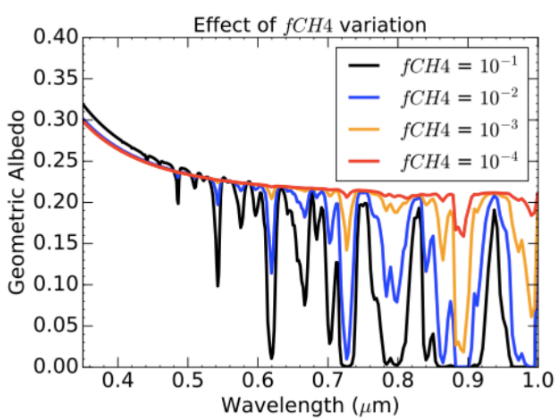
WFIRST
Wide-Field Infrared Survey Telescope
Astrophysics • Dark Energy • Exoplanets

CGI potential science areas

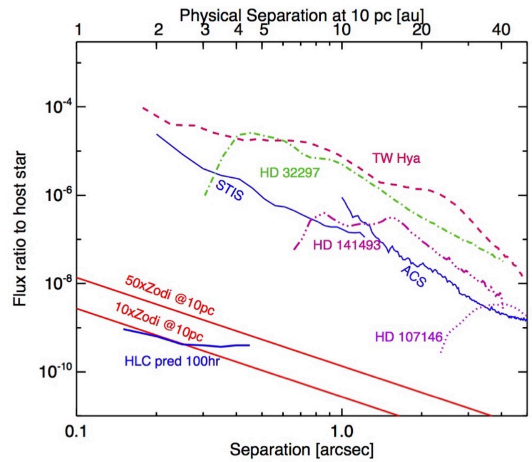
Self-luminous, young super Jupiters: atm. properties

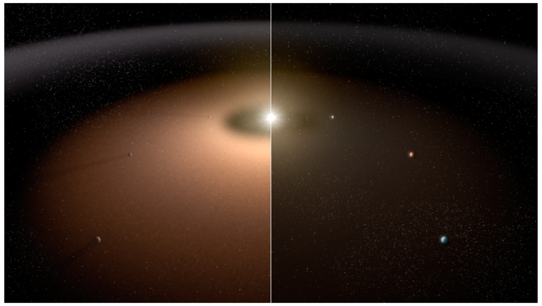


Mature Jupiter analogues in reflected light: mass & CH_4

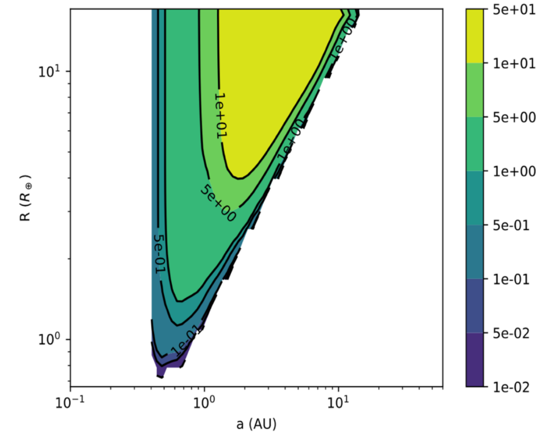


Circumstellar disks: Protoplanetary (young) Debris (mature) Exozodi (mature, HZ)





Possible blind searches for giant planets



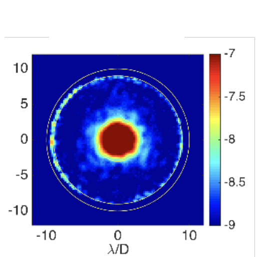
Possible characterization of Habitable Zone of nearby systems

CGI Official Modes

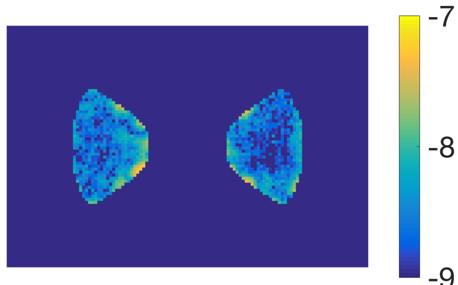
These three "official" modes will be fully commissioned before launch.
ie: the flight hardware will by fully tested with flight software prior to launch.

CGI Filter	λ_{center} (nm)	BW	Channel	Mask Type	Working Angle	Can use w/ linear polarizers	Starlight Suppression Region
1	575	10%	Imager	HLC	3-9 λ/D	Y	360°
3	760	18%	IFS	SPC bowtie	3-9 λ/D		130°
4	825	10%	Imager	SPC wide FOV	6.5-20 λ/D	Y	360°

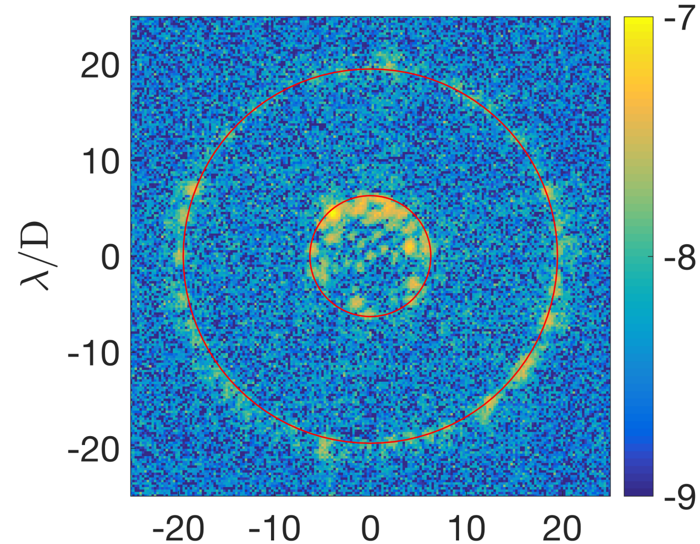
Imaging w/ Narrow FoV
HCIT Lab Image



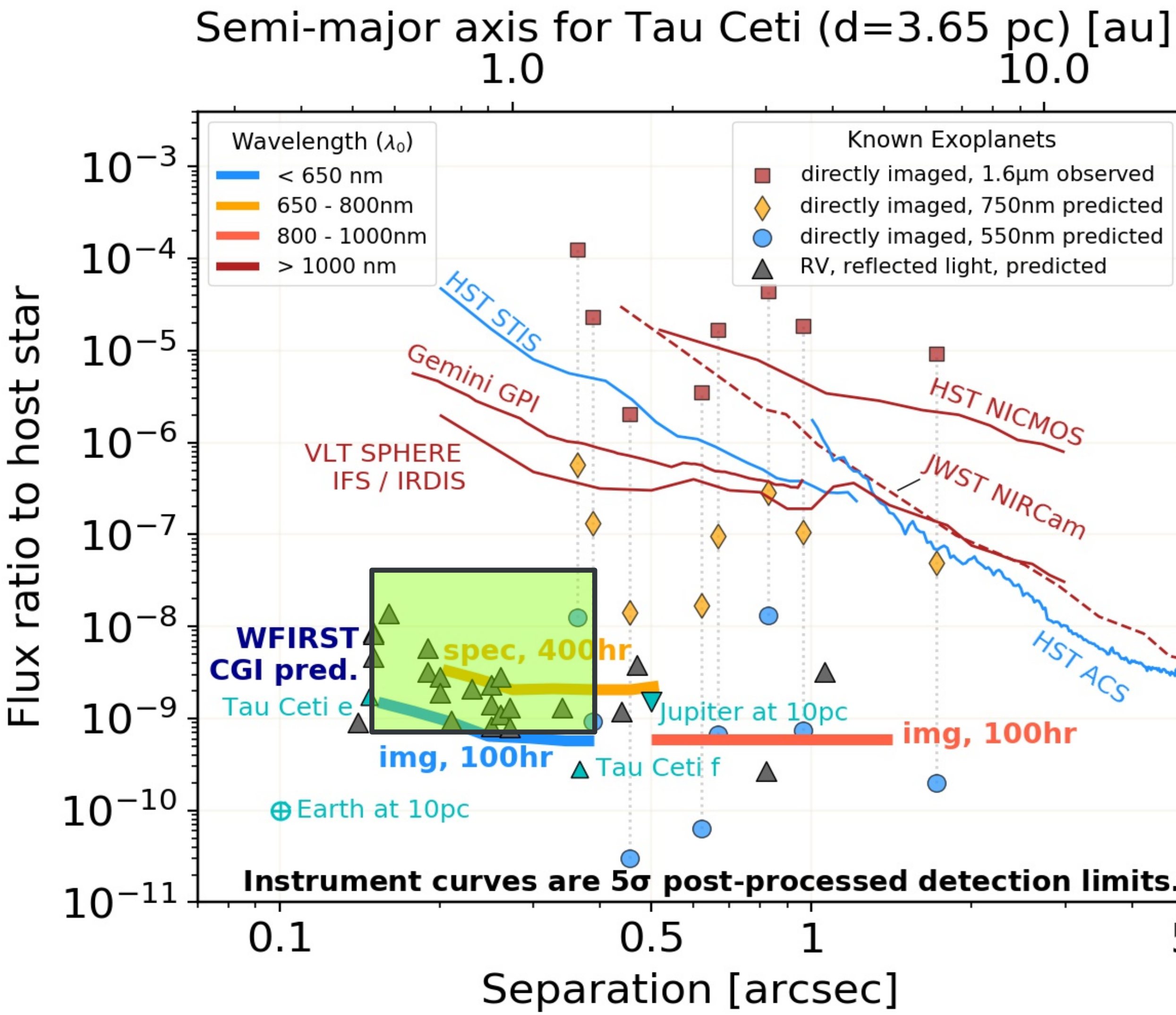
Spectroscopy
HCIT Lab Image

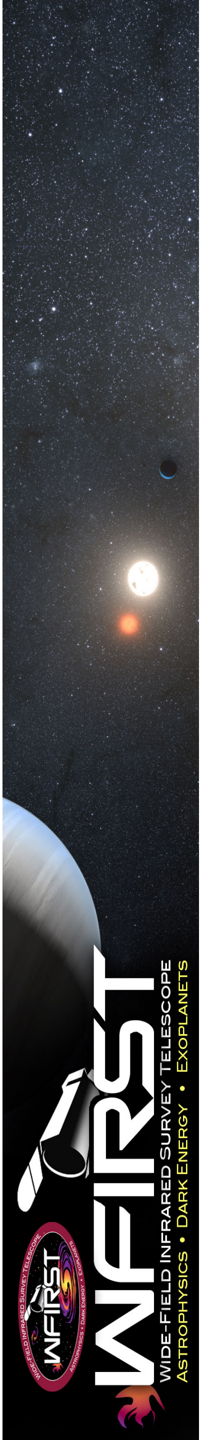


Imaging w/ Wide FoV
HCIT Lab Image

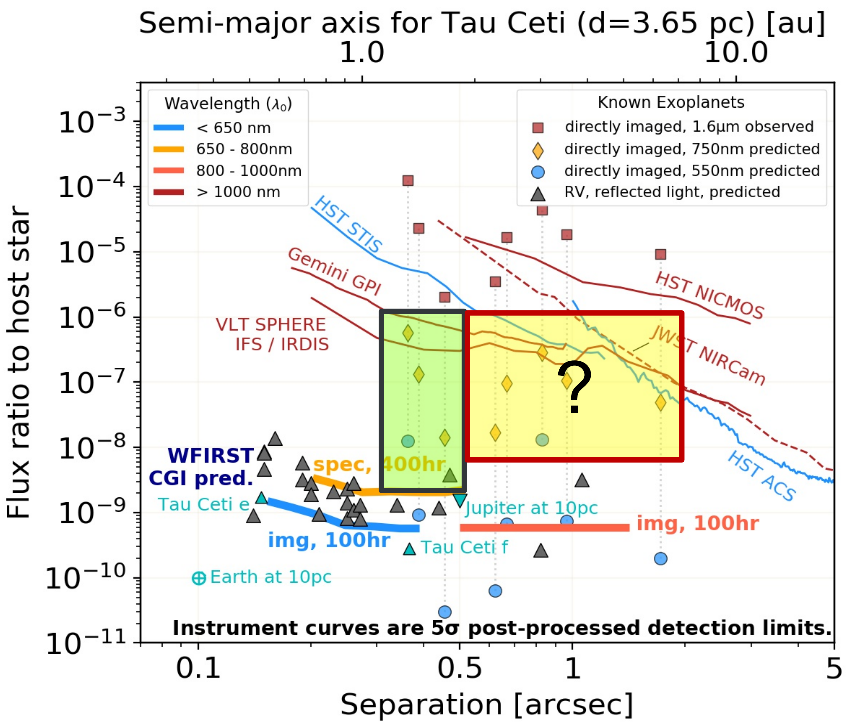


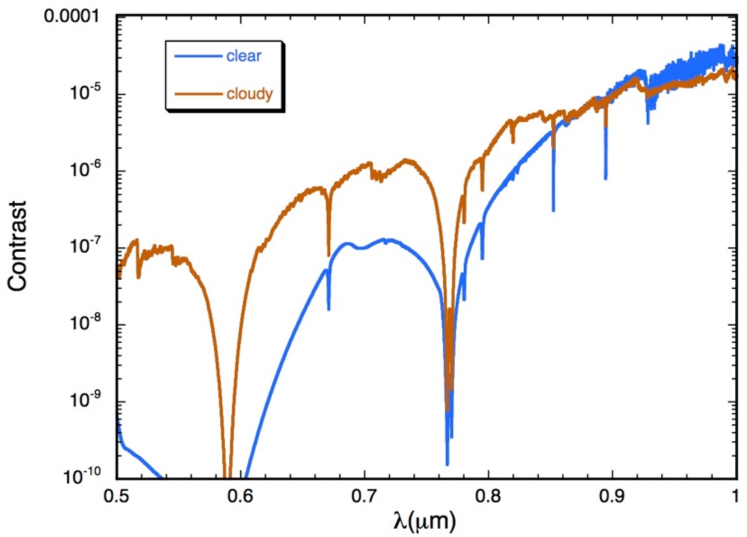
Break vsin(i) mass degeneracy for RV planets with reflected light imaging





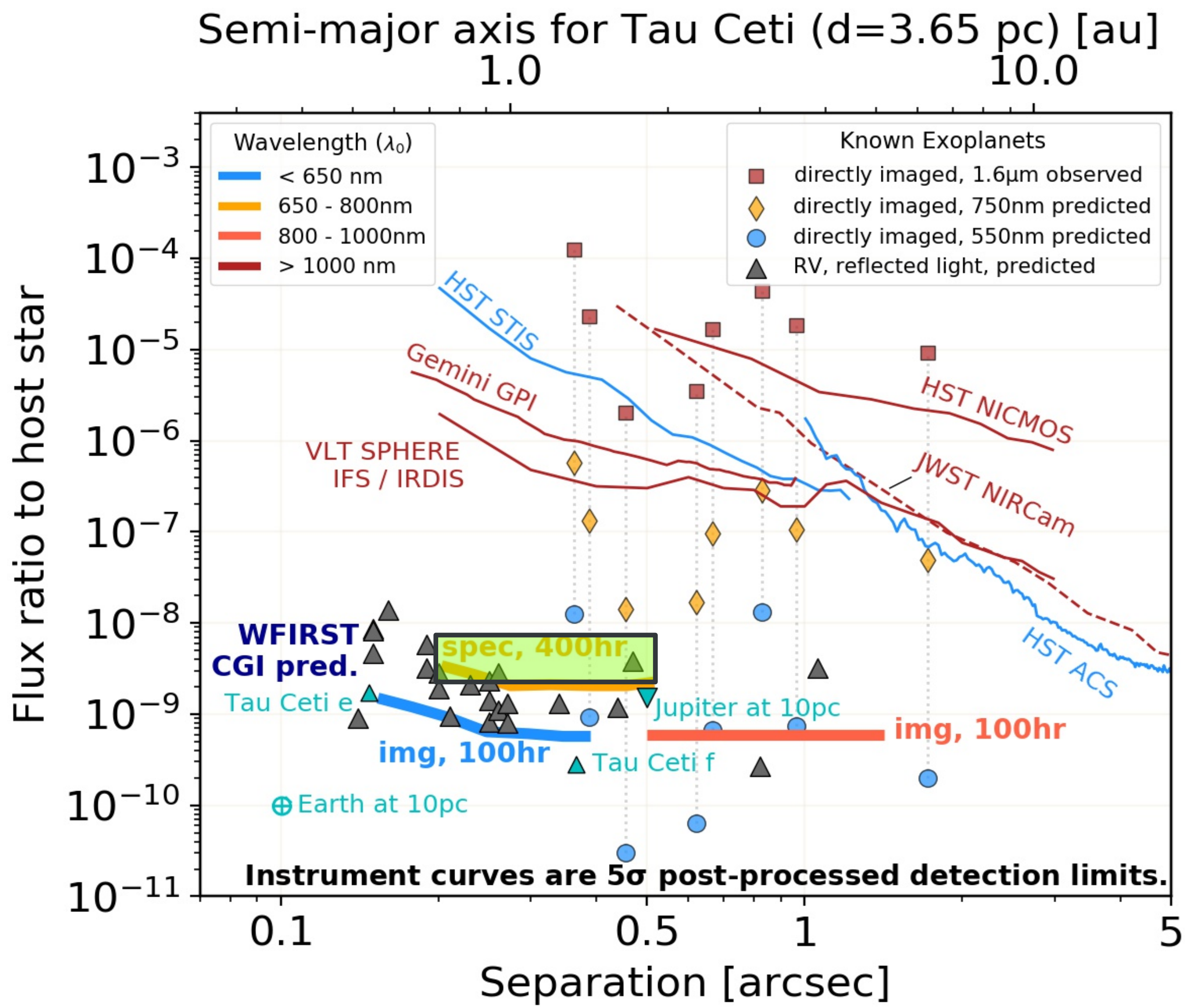
Spectra of young self-luminous planets: Beta Pic b, HR 8799 e, 51 Eri b

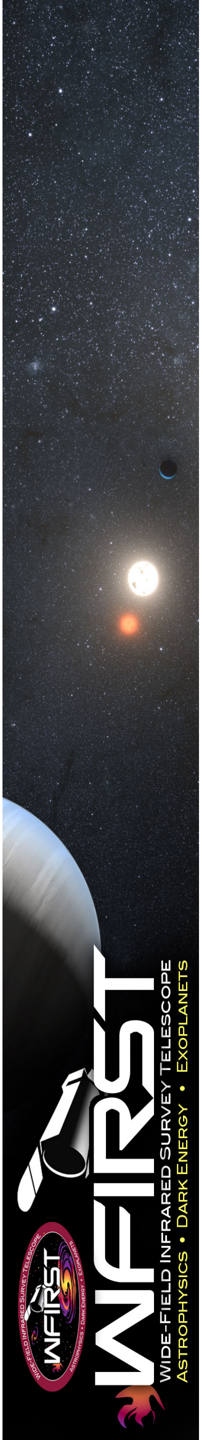




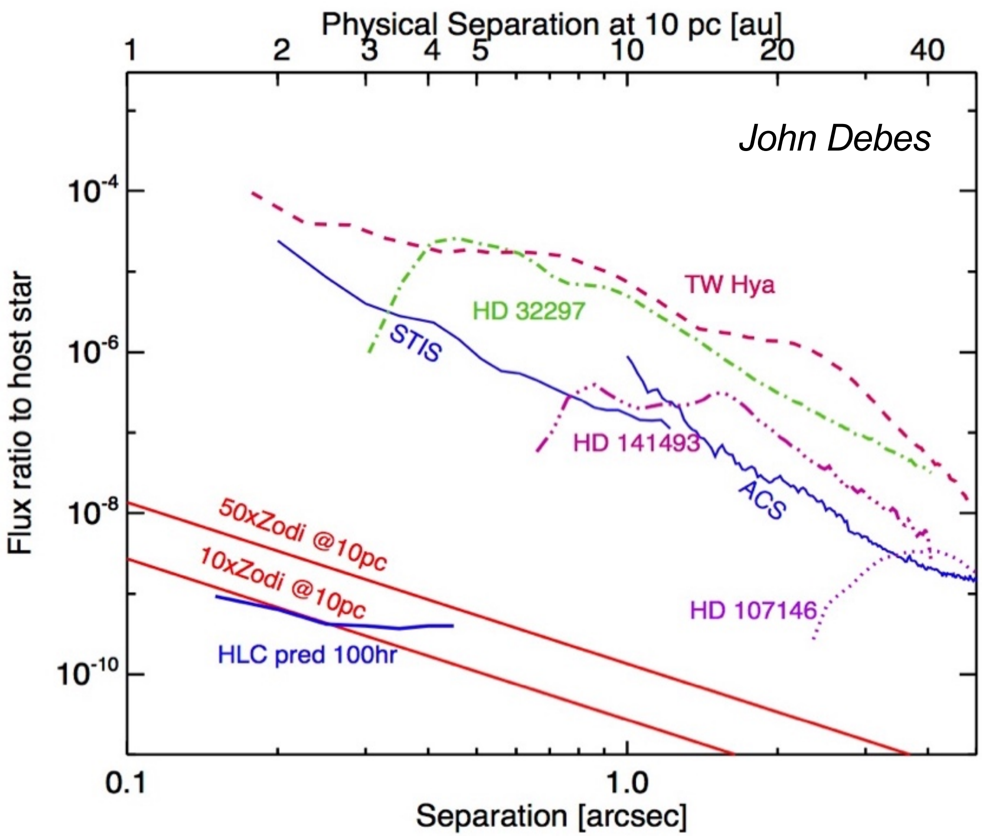
- CH4 abundance
- Cloud properties
- Halpha accretion?

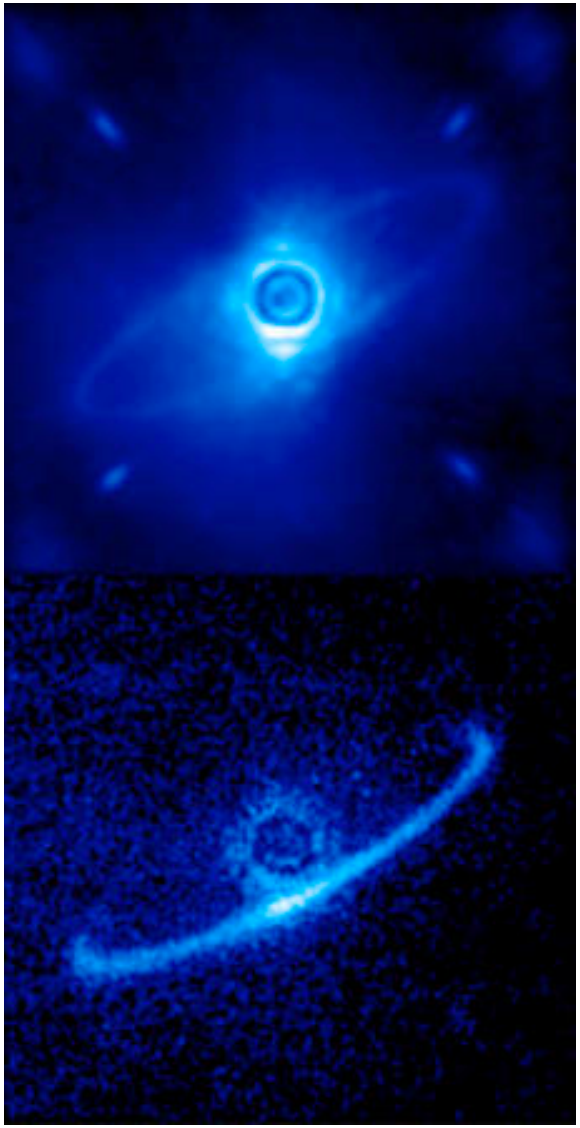
Reflected light spectroscopy of mature RV planets



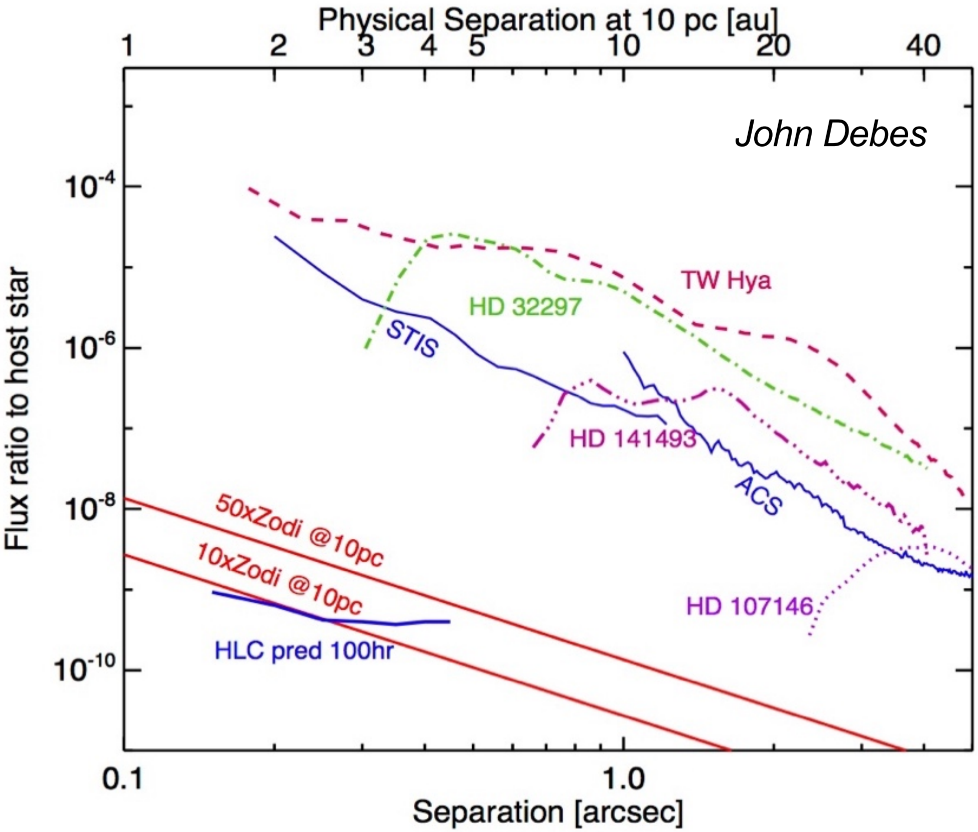


Imaging and Polarimetry of Debris Disks

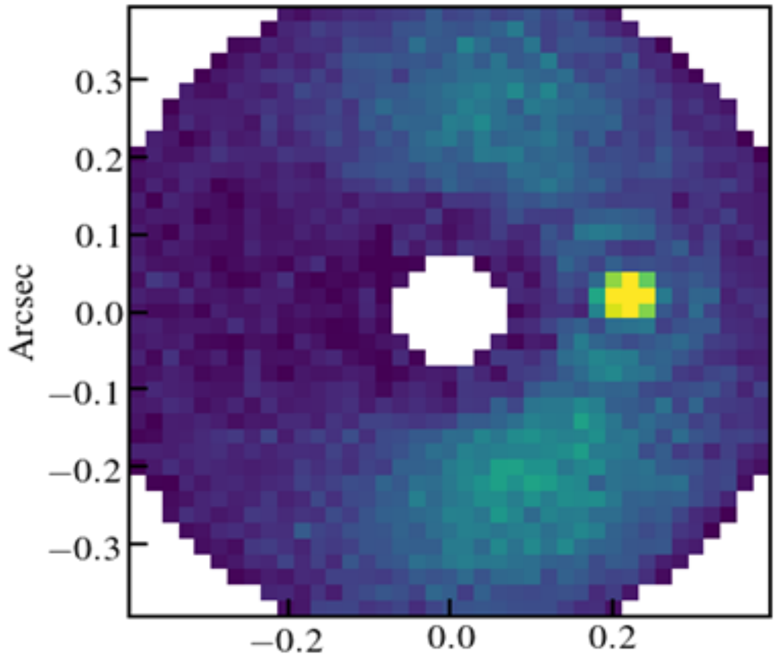




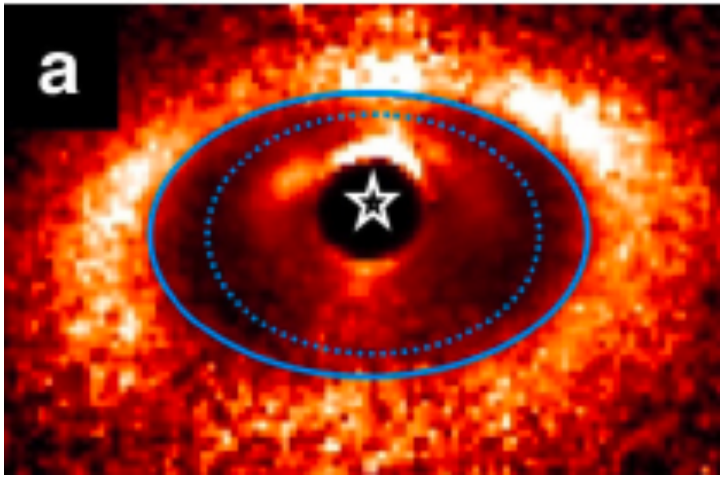
Exozodi : contaminants & targets



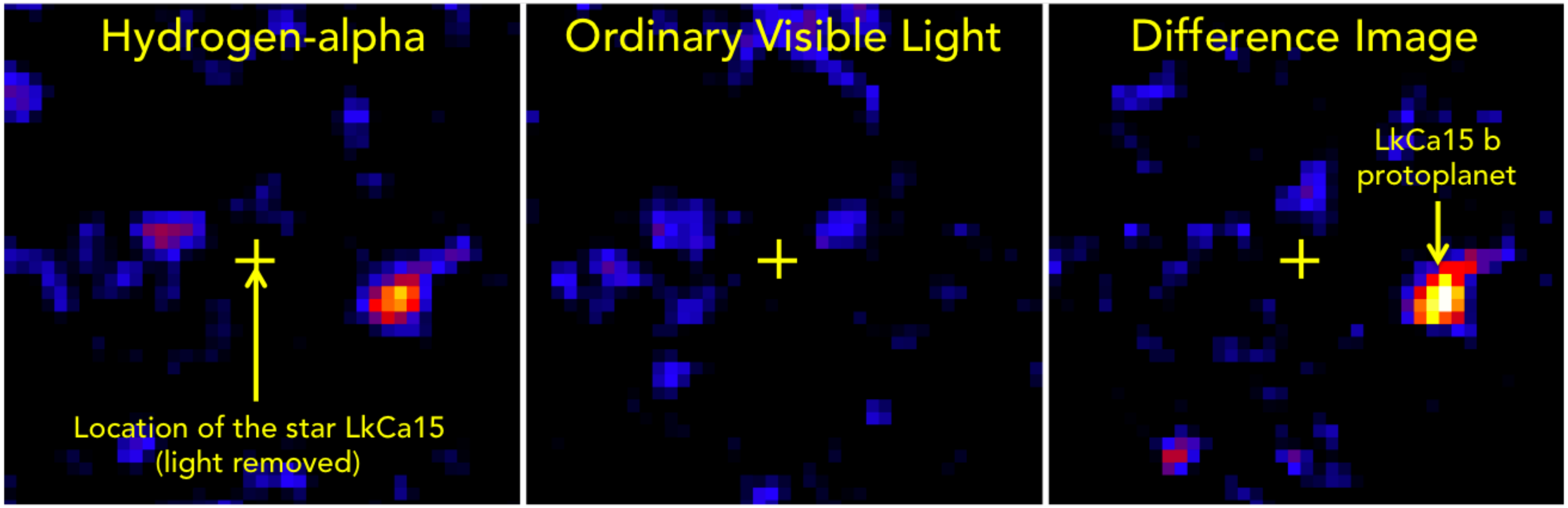
M. Rizzo, N. Zimmerman and the "Haystacks" team.
10zodi disk & embedded jovian planet located at 1.6 AU



Maybe: Protoplanetary disks & protoplanets

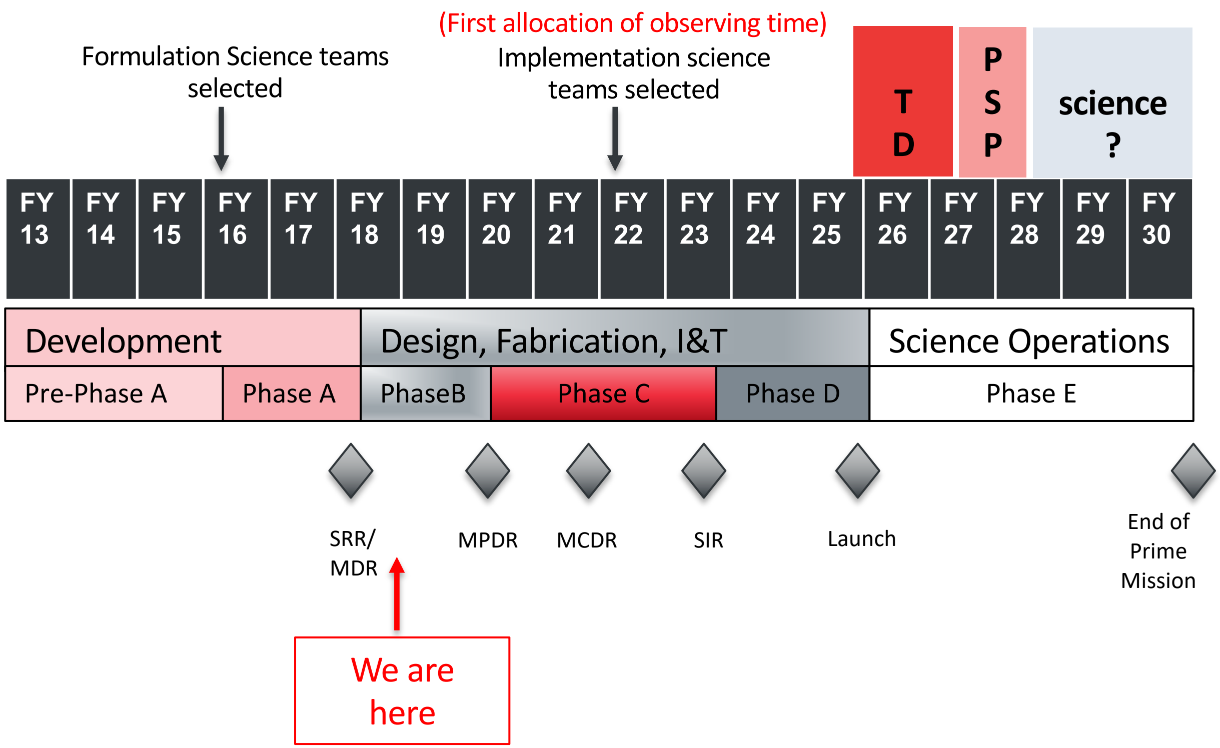


Thalmann et al. (2016)



Sallum et al. 2015

Project Schedule



- **3 months** of *guaranteed* "tech demo" observing in first **1.5 years** of mission
- *If successful*, **1 year Participating Science Program (shared** w/ WFI)
- *If successful*, follow-on **2.5 year (shared) science program**
- Potential for extended mission for years 5-10?

(Very) rough draft observing plan for tech demo phase

- Required:
  - 575nm images of several reflected light Jupiters and circumstellar disks
  - 730nm spectrum of 1 reflected light Jupiter and 1 self-luminous Jupiter or brown dwarf
  - 825nm imaging of 1 faint debris disk & polarimetry of 1 breight debris disk
- Perhaps:
  - 575nm image 1-2 exozodi
  - imaging of protoplanetary disk(s)
  - H_{alpha} imaging of protoplanet

National Academy of Science: Exoplanet Science Strategy, Sept 2018

WFIRST Will Provide Critical Exoplanet Data and Pave the Way for a Direct-Imaging Mission

FINDING: A microlensing survey would complement the statistical surveys of exoplanets begun by transits and radial velocities by searching for planets with separations of greater than one AU (including free-floating planets) and planets with masses greater than that of Earth. A wide-field, near-infrared (NIR), space-based mission is needed to provide a similar sample size of planets as found by Kepler.

FINDING: A number of activities, including precursor and concurrent observations using ground- and space-based facilities, would optimize the scientific yield of the WFIRST microlensing survey.

FINDING: Flying a capable coronagraph on WFIRST will provide significant risk reduction and technological advancement for future coronagraph missions. The greatest value compared to ground testing will come from observations and analysis of actual exoplanets, and in a flexible architecture that will allow testing of newly developed algorithms and methods.

FINDING: The WFIRST-Coronagraph Instrument (CGI) at current capabilities will carry out important measurements of extrasolar zodiacal dust around nearby stars at greater sensitivity than any other current or near-term facility.

RECOMMENDATION: NASA should launch WFIRST to conduct its microlensing survey of distant planets and to demonstrate the technique of coronagraphic spectroscopy on exoplanet targets.

The National Academies of SCIENCES ENGINEERING MEDICINE

Project Status

- KDP-B completed May 22, 2018
  - **WFIRST now in Phase B!**
  - <u>*WFI*</u> Integral Field Channel descoped – 4/27/2018 (CSA Budget Constraints)

- White House FY2019 budget proposed termination of WFIRST to fund other priorities
- Direction from HQ is to proceed while Congress deliberates
  - *Preliminary indications are that WFIRST will be fully funded in FY2019*

- Notional schedule:
  - PDR: late 2019
  - CDR: mid 2021
  - **Launch: 3rd quarter 2025**

Summary

- CGI is a **technology demonstrator**
  - first “active” coronagraph in space
  - Important pathfinder for future missions to study exo-Earths

- CGI is capable of interesting science
  - Imaging & spectroscopy of young & mature planets
  - Imaging & polarimetry of debris disks, exozodi, & protoplanetary disks

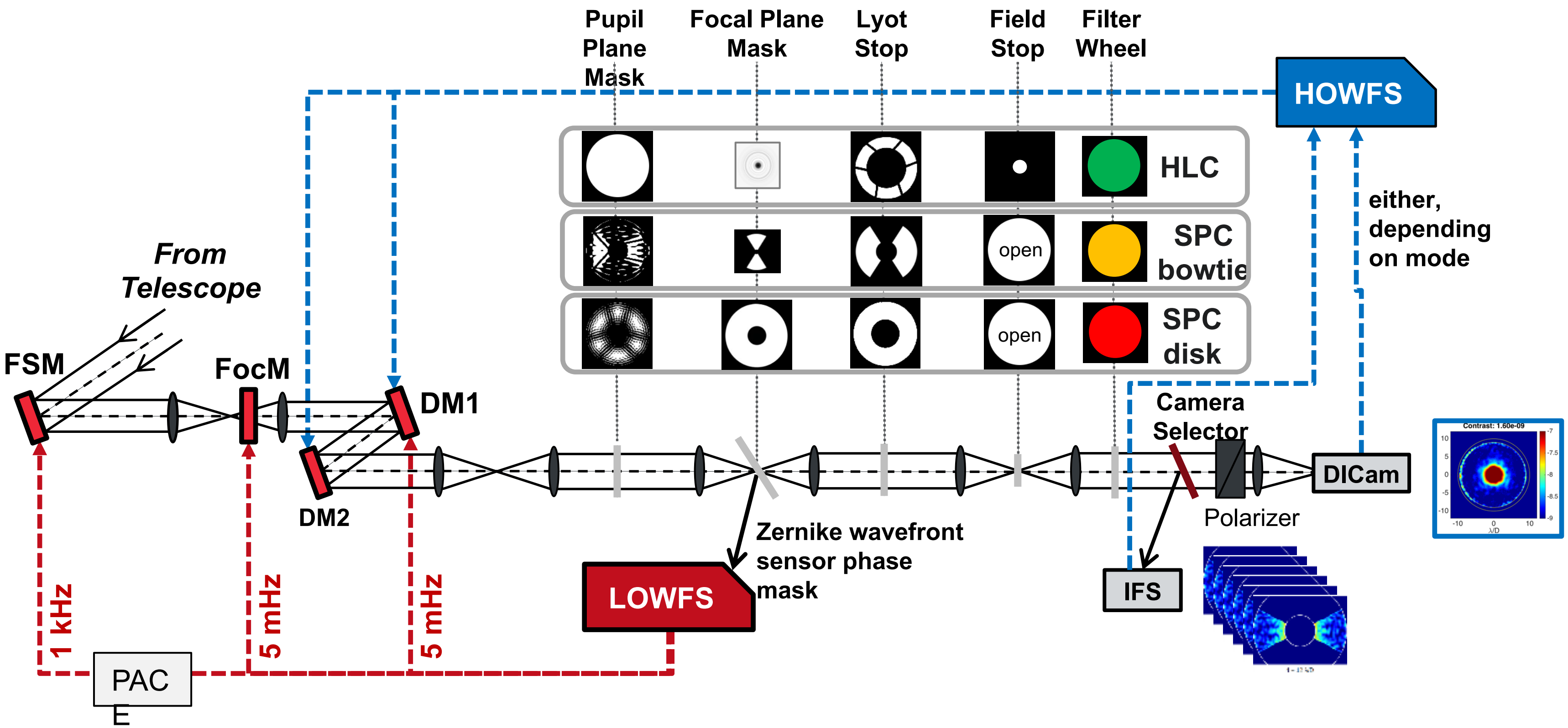
- Notional observing program
  - **Guaranteed:** 3 months of tech demo observing in first 1.5 years of WFIRST mission
  - **If meet success criteria**, 1 year Participating Science Program
    - Calls for PSPs expected ~2020
    - Shared w/ WFI
  - **If PSP is successful**, follow-on 2.5 year science program
    - Shared w/ WFI

Exoplanets:
Detections by Discovery Year

1989-2018

Plots generated Sept. 27, 2018

CGI Architecture

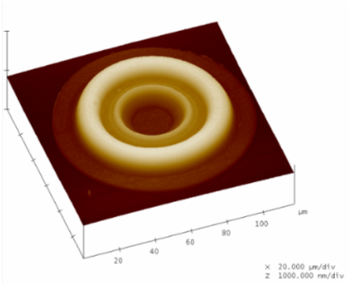


- Two selectable coronagraph technologies (HLC, SPC)
- Two deformable mirrors (DMs) for high-order wavefront control
- Low-order wavefront sensing & control (LOWFS&C)
- Direct imaging camera (DICam)
- Integral field spectrograph (IFS, R = 50)
- Photon-counting EMCCD detectors

Successful Technology Maturation for CGI

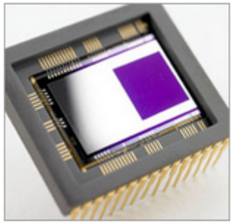
- Pupil plane and focal plane masks for starlight suppression
  - Hybrid Lyot Coronagraph (HLC)
  - Shaped Pupil Coronagraph (SPC)
- Photon-counting electron-multiplying (EM) CCD for detection of very faint planets
  - Teledyne e2v
  - 1K×1K pixels
  - Radiation characterization
- Deformable mirrors for telescope surface error and drift correction
  - Northrop Grumman Xinetics
  - 48×48 actuators
  - Electrostrictive PMN (lead magnesium niobate)
  - Still requires environmental test of interconnect
- Coronagraph system-level performance demonstrated using a testbed with flight-like observatory disturbances:
  - Optical telescope simulator, with simulated pointing and thermal drift errors
  - High-order wavefront sensing and control to system to measure/correct telescope errors
  - Low-order wavefront sensing and control system to measure/correct telescope drift and provide tip/tilt error signal

HLC mask image with an atomic force microscope

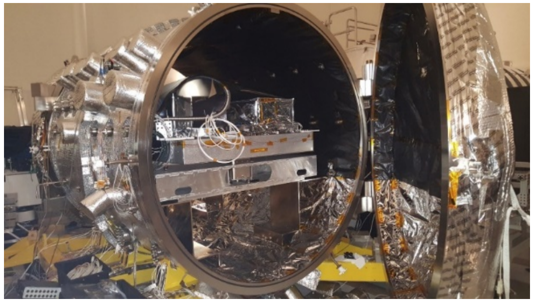


SPC mask image with an atomic force microscope

Xinetics 48 x 48 DM used in JPL's HCIT



E2V EMCCD used in photon-counting mode



Testbed
JPL's High Contrast Testbed

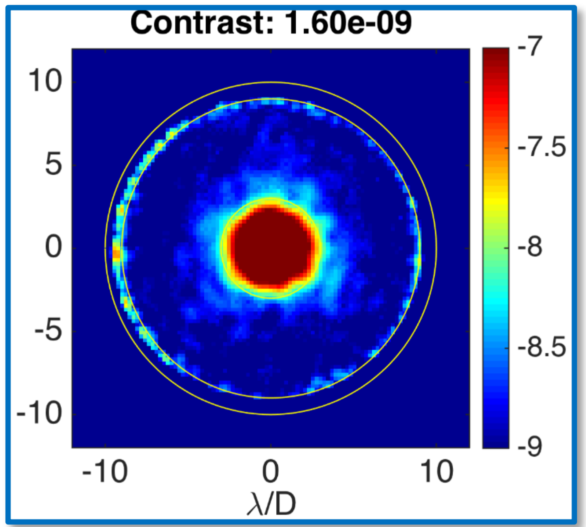
CGI Coronagraphs

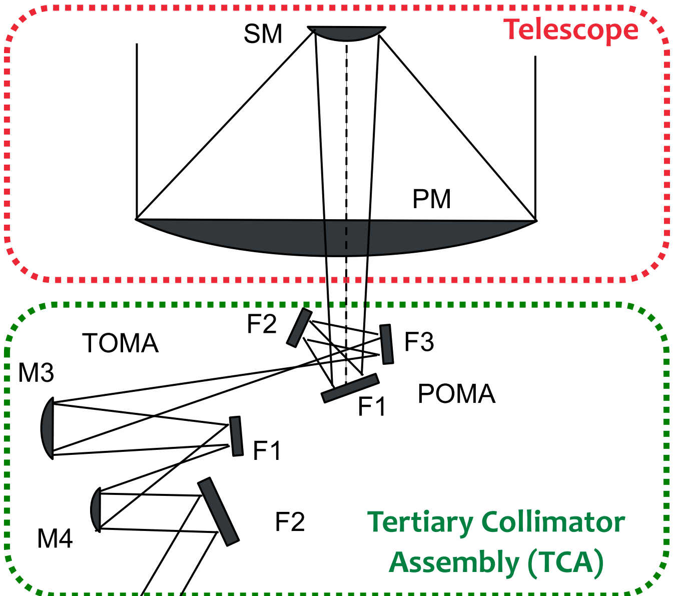
CGI Filter	λ_{center} (nm)	BW	Mask Type	Working Angle	Starlight Suppression Region
1	575	10%	HLC	3-9 λ/D	360°
2	660	18%	SPC bowtie	3-9 λ/D	130°
3	760	18%	SPC bowtie	3-9 λ/D	130°
4	825	10%	SPC wide FOV	6.5-20 λ/D	360°
4	825	10%	HLC	3-9 λ/D	360°

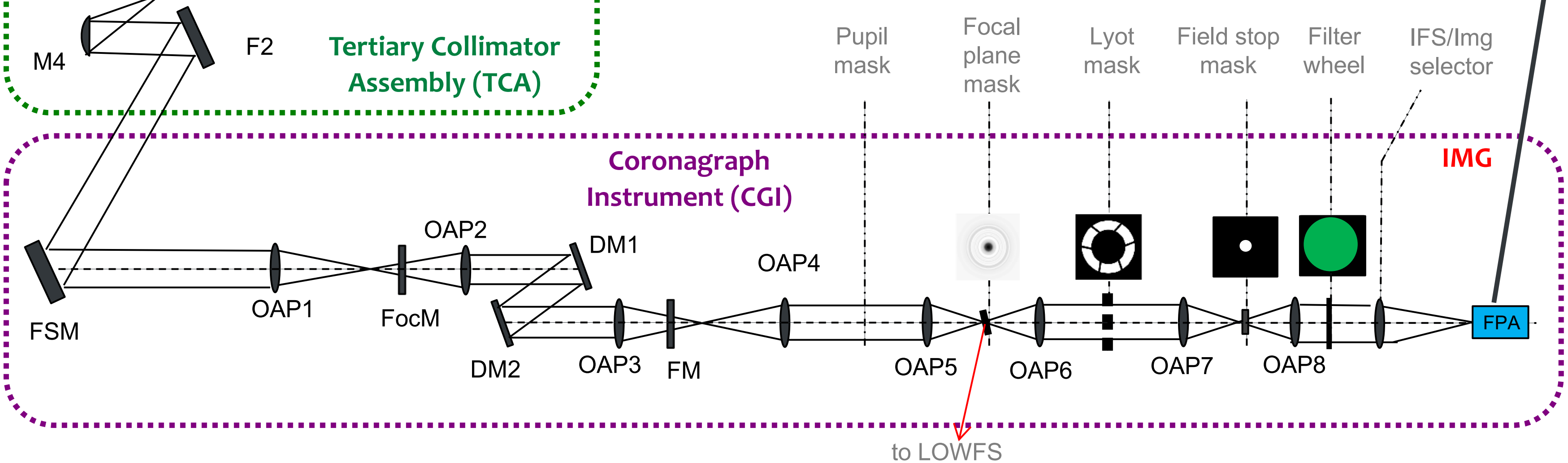
These five coronagraph masks will be installed in CGI. However, only the three CGI configurations supporting the “official observing modes” will be fully tested for the tech demo phase.

Imaging with Narrow Field of View Mode

Dark hole for planet photometry and discovery centered at 575 nm with annular FOV from 3-9 λ/D

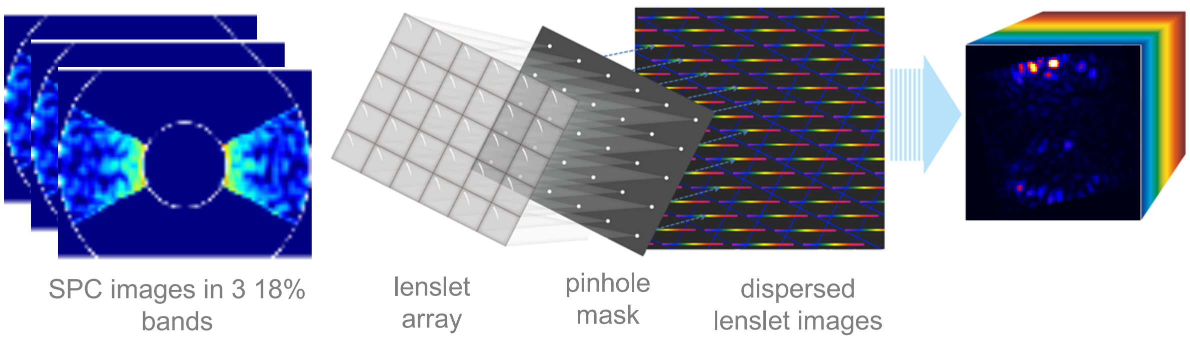


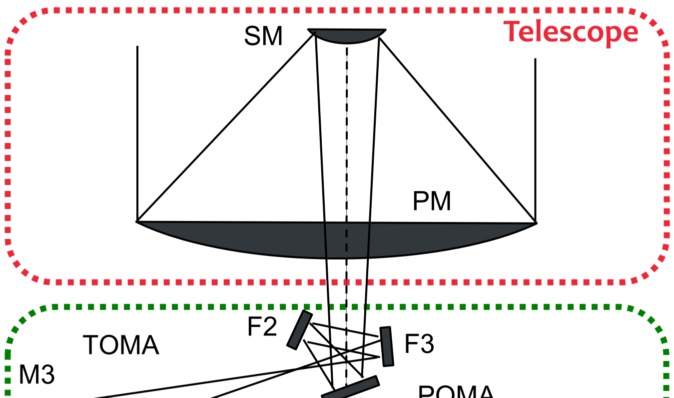


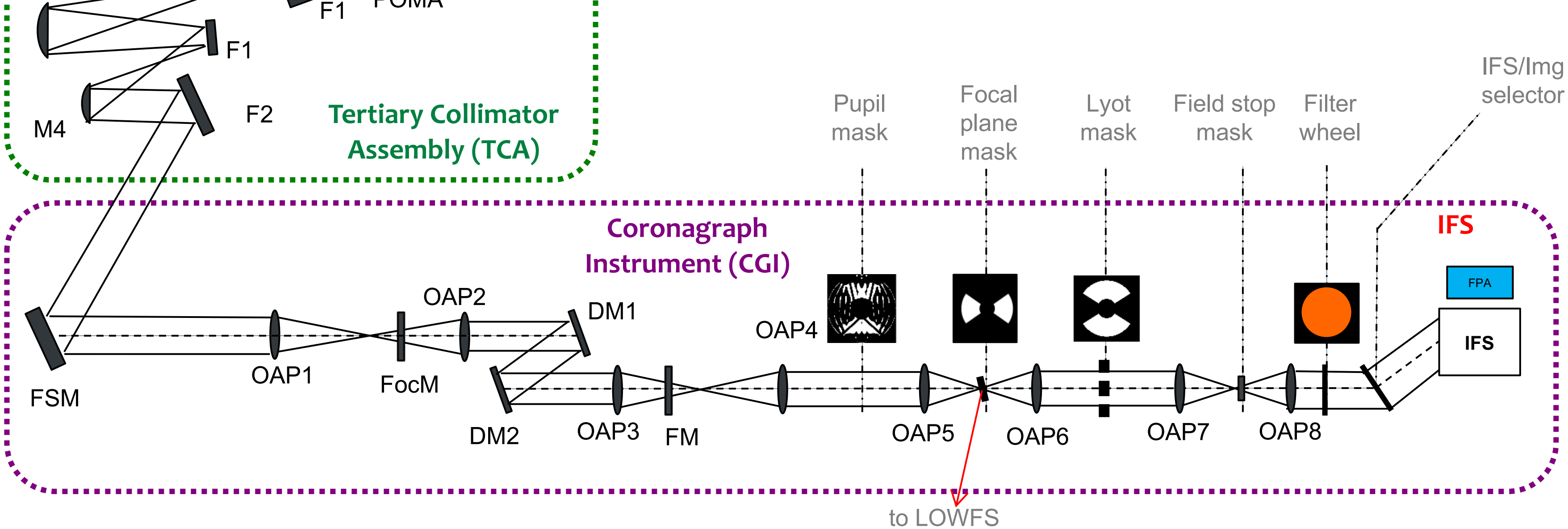


Spectroscopy Mode with Integral Field Spectrograph (IFS)

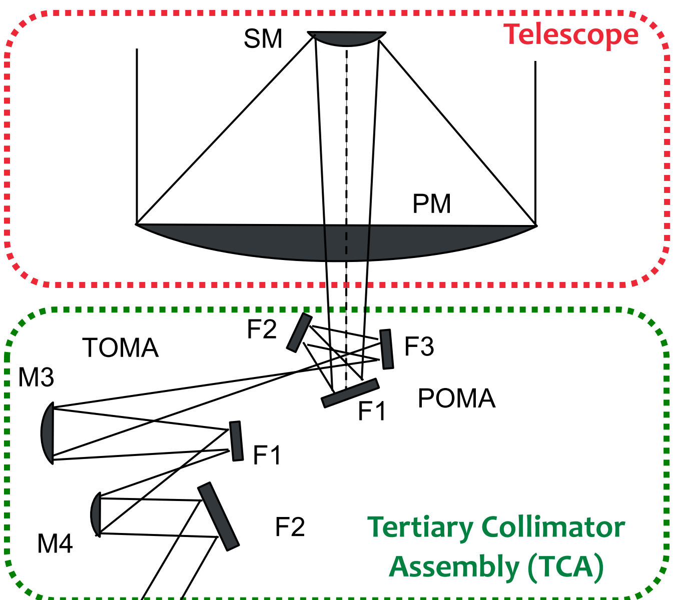
The IFS uses 3 18% bands to produce R=50 spectra from 600 to 830 nm







Imaging with Wide Field of View Mode



Disk imaging at wavelengths 508 and 721 nm, with outer working angle of 20 λ/D

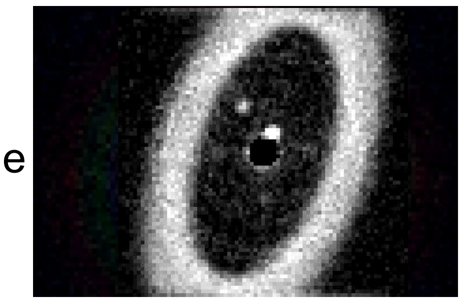
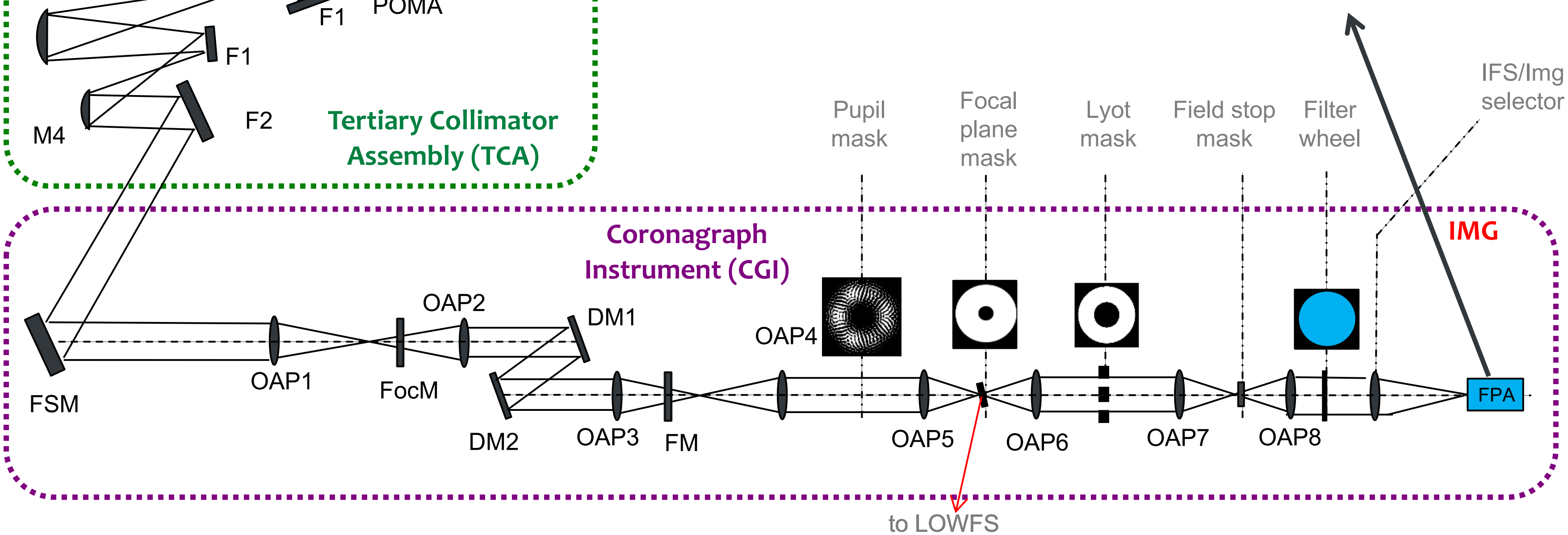


Image from 2015 Exo-C STDT Final Report



Observation: Integration and Chop Cycle

Bright Reference Star
Dig dark hole &
PSF reference

Science Target
Roll A

Science Target
Roll B